The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow and groundwater resources

AD Clulow, CS Everson & MB Gush

WATER RESEARCH COMMISSION

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THE LONG-TERM IMPACT OF *ACACIA MEARNSII* TREES ON EVAPORATION, STREAMFLOW AND GROUNDWATER RESOURCES

Report to the
WATER RESEARCH COMMISSION

by

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LIST OF ABBREVIATIONS AND SYMBOLS

Roman symbols

C_n^2	structure parameter of refractive index	$m^{-2/3}$
d	zero plane displacement height	m
ET	total evaporation	mm
ET_{LAS}	LAS-based total evaporation	mm
ET_{P-T}	Priestley-Taylor-based total evaporation	mm
ET_{sz}	ASCE-EWRI short grass (0.12 m) reference evaporation	mm
F_h	sensible heat flux	$W\ m^{-2}$
h	water potential	
L_vF_w	latent energy flux	$W\ m^{-2}$
$L_vF_{w(P-T)}$	Priestley-Taylor-based latent energy flux	$W\ m^{-2}$
n	number of samples	
P_{UCN2}	Scaled C_n^2 ($C_n^2 = P_{UCN2}$ x 10-^{15})	$m^{-2/3}$
Q	Streamflow	mm
R	Rainfall	mm
R_n	net irradiance	$W\ m^{-2}$
T	air temperature	ºC
T_z	air temperature at height z above the ground	ºC
U_{CN2}	Log C_n^2 signal	$m^{-2/3}$
z_o	roughness length	m

Greek symbols

α	curve fitting parameter	
β	Bowen ratio	
Δ	slope of saturated vapour pressure vs air	kPa $ºC^{-1}$
ΔS	change in soil water storage	mm

γ	psychrometric constant	kPa ºC^{-1}
θ	actual volumetric water content	m^3 m^{-3}
θ_m	mass water content	kg^3 kg^{-3}
θ_r	residual volumetric water content	m^3 m^{-3}
θ_s	saturated volumetric water content	m^3 m^{-3}
θ_v	volumetric water content	m^3 m^{-3}
ρ_s	bulk density of soil	kg m^{-3}
ρ_w	density of water	kg m^{-3}

Abbreviations

ASCE	American Society of Civil engineers
ASCE-EWRI	American Society of Civil Engineers – Environmental and Water Resources Institute
ACRU	Agricultural Catchment Research Unit
AWS	Automatic weather station
CSIR	Council of Scientific and Industrial Research
DWAF	Department of Water Affairs and Forestry
FAO-56	Food and Agriculture Organisation, paper no. 56
GIS	Geographic information system
GPS	Global positioning system
ISCW	Institute for Soil, Climate and Water
LAI	Leaf area index
LAS	Large aperture scintillometer
LED	Light emitting diode
MAP	Mean annual precipitation
PAW	Plant available water
RAW	Readily available water
RETC	Retention Curve Program
TDR	Time domain reflectometry
VPD	Vapour pressure deficit
WAVES	Water, Vegetation, Energy, Solute

EXECUTIVE SUMMARY

1. Motivation

Good estimates of tree water-use and the impacts thereof are critical to the forestry industry and equitable water supply to all South Africans. In this study, state-of-the-art technology was applied to quantify the water-use of trees and assess whether there was a potential long-term impact on water resources.

2. Project objectives

The specific objectives of the project were to:

- quantify the long-term effects of commercial forestry species on deep soil water profiles, streamflow and evaporation;
- describe the controlling environmental and soil water processes which allow for total evaporation to exceed the annual rainfall;
- provide a modelling framework for the catchment water balance to improve stream flow predictions and specifically low flows; and
- extend the hydrological record of the Two Streams catchment experiment to provide a long-term database of the catchment hydrological variables for future modelling studies.

3. Background

The Two Streams catchment experiments have been used over the last nine years to study the impact of trees on hydrological processes. Burger (1999), for example, estimated total evaporation using the Bowen ratio energy balance method and showed that annual total evaporation exceeded annual rainfall when measured over *Acacia mearnsii* at Two Streams during the exponential growth phase. This suggested that either the instruments used were providing incorrect results, or that tree roots were accessing groundwater and depleting soil water reserves from within the deep soil profile. Everson *et al*. (2008) showed the significant impact that riparian zone management can have on the hydrology of the catchment.

Currently the regulation of water-use by forestry is based on estimates of plantation water-use over entire rotations at quaternary catchment scale (Gush *et al*., 2002), which are average values that are not site or age specific. In addition the model used, Agricultural Research Catchment Unit (ACRU), did not account for soil water depletion at depths greater than 1.2 m. Gush *et al*. (2002) concluded that our understanding of the hydrological processes with regard to the water-use of trees from deep soil profiles was inadequate.

These experiments provided a good opportunity for studies to extend our understanding of some of the hydrological processes associated with afforestation such as low flows and deeper soil water dynamics.

4. Methods

The research catchment was situated at the Mistley-Canema Estate (Mondi Forests) approximately 70 km from Pietermaritzburg. The catchment had been fallow for two years since 2004 and was planted to a new rotation of *Acacia mearnsii* trees in 2006. This provided an opportunity to monitor the water balance of the catchment during the establishment of the trees and the initial growth phases of the plantation crop for a two and a half year period.

4.1 Tree growth

Tree heights were measured along the path of the scintillometer at 30 points through the plantation. To accurately monitor the high growth rate of the trees, heights were measured at monthly intervals.

Leaf area index (LAI) of the tress was measured using a LiCor LAI-2000 leaf area meter. When the trees reached two metres, a second LAI-2000 leaf area meter was run in combination with the first to capture above and below canopy radiation simultaneously and combined with the first to calculate LAI.

Root growth was assessed by hand auguring to depths of 4.8 m. Samples were collected and sieved in order to extract the root material.

4.2 General climatic variables

Campbell Scientific weather stations were used to monitor solar radiation, air temperature, relative humidity, rainfall, wind speed and wind direction. One station, historically used at Two Streams over Sugarcane, was maintained at the site for the long-term record. A new station was sited to conform specifically to the requirements of a short grass reference standard evaporation. A third station was mounted above the trees and, in addition to the standard weather station measurements, sensors for measurements of the soil heat flux and net radiation were included.

Rainfall was monitored at an additional two sites in the catchment using tipping bucket raingauges connected to event Onset Hobo dataloggers.

4.3 Evaporation

The shortened energy balance equation was used to estimate the daily total evaporation in the catchment from August 2006 to December 2008. Net radiation and soil heat flux were measured directly. Sensible heat flux was estimated using a Kipp and Zonen large aperture scintillometer (LAS) transmitter and receiver. The transmitter and receiver were mounted on towers that were extended as the tree height changed. The effective height of the LAS above the tree canopy was calculated at two-weekly intervals due to the fast growth rate of the trees.

4.4 Streamflow

Streamflow was monitored continuously in the main catchment; initially using a 457.2 mm, 90° V-notch weir with a Belfort Streamflow recorder modified with an MCS 250-01 streamflow encoder. This was later replaced with an Ott Streamflow recorder and pressure transducer. A sieve was installed to prevent debris blocking the V-notch.

4.5 Soil water dynamics

Intensive soil water measurements were performed using various methods. Initially CS616 Water Content Reflectometer probes were used to capture the soil water changes while modified deep time domain reflectometer (TDR) probes were being developed. The CS616's were installed by digging a pit to a depth of 2.5 m and inserting the sensors at 0.4 m intervals to a depth of 2.4 m.

Time domain reflectometry probes operated with a Campbell Scientific TDR100 were designed for installation at depths in excess of 2.0 m. They were cylindrical in shape, had three short wave-guides and the head of the probe was moulded with a strong resin so that the probes could be hammered into the ground. They were installed at 0.4 m intervals to a depth of 4.8 m using a hand-auger.

During the course of the project, in order to confirm volumetric water content results, watermark sensors manufactured by Irritol Corporation were installed near the cylindrical TDR probes also to a depth of 4.8 m.

4.6 Water balance

A monthly water balance for the catchment was calculated based on rainfall, streamflow, evaporation and actual change in soil water storage to a depth of 2.4 m. The overall change in soil water storage was calculated as the residual of the water balance equation.

4.7 Hydrological modelling

The Water, Vegetation, Energy, Solute (WAVES) and revised Intermediate-Zone ACRU models were used to predict the soil profile water contents. The Intermediate-Zone ACRU model was also used to predict the streamflow in the catchment. The modelled results of soil profile water content and streamflow were compared to the measured values.

5. Results and discussion

Tree growth was consistent and did not fluctuate seasonally indicating that the trees were not stressed during drier months. Tree height growth over 30 months averaged 0.37 m month^{-1} or 4.5 m year^{-1} from planting to a height of approximately 11.2 m. Canopy leaf area measurements initially included a large contribution from tall weeds in summer 2006 to 2007. The weeds died off in winter 2007 and the LAI showed a steep rise to 2.5 in December 2007 when canopy closure was reached. Root samples were taken using a hand auger to a depth of 4.8 m in February 2008 and February 2009. There was a noticeable increase in the root mass (g kg^{-1} of soil) in 2009 at a depth of 3.2 m and roots were found at depths of 4.8 m.

The nine year average annual rainfall from 1999 to 2008 was 920 mm. The annual rainfall at the study site was highly variable with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm).

Mean annual runoff (MAR) between 2001 and 2008 was 48 mm with an annual maximum of 91 mm in 2005 (when the mean annual precipitation (MAP) was 1139 mm) and an annual minimum of 6.7 mm in 2003 (when the MAP was 659 mm). Streamflow was a relatively small fraction of the rainfall although this relationship changed in 2005 after clear-felling of the catchment. In 2001 to 2004 the average ratio was 0.03. After the catchment was clear-felled in 2004, the average ratio changed to 0.08.

The results from all the soil water methods were typical of a deep soil profile with high variability at the surface and less variability at depth. The soil profile was however driest at 1.6 m according to the cylindrical TDR probes and the Watermark sensors. Water content from 2.4 m to 4.8 m increased with depth. There was however, little or no recharge during the wet seasons which resulted in a steady reduction in volumetric water content to December 2008. The water content at 4.8 m was close to field capacity (45%).

The LAS estimates of daily total evaporation (ET_{LAS}) values ranged from 0 mm on rainy days to 6 mm on cloudless days for the first summer and 7 mm and 9 mm for the second and third summers respectively. On clear winter days the maximum total evaporation was 2.2 mm day^{-1} in 2007 and 2.4 mm day^{-1} in 2008. Monthly totals of total evaporation (*ET)* showed clear seasonal trends. Over the three-year period from 2006 to 2008 there was an exponential increase in the *ET* totals in the main growing period (October to December) from 305 mm, 334 mm and 417 mm for years 2006, 2007 and 2008 respectively. The 25% increase from 2006 to 2008 is ascribed to the high LAI (canopy closure) recorded in 2008.

The LAS estimates of total evaporation were verified using the Priestley-Taylor (1972) estimates of latent energy flux with an *α* (which represents the advective term) of 1.26. There was a significant (R^2 = 0.94) linear relationship between the daily ET_{LAS} and $ET_{P\text{-}T}$ indicating that the trees at Two Streams were seldom stressed or subjected to advection. The Priestley-Taylor method therefore represented a simple and realistic descriptor of *A. mearnsii* water-use for trees up to three years old. This relationship may not be valid in other climatic areas where trees may experience water-stress.

Regression analysis between reference evaporation (ET_{sz}) and ET_{LAS} showed close agreement with a coefficient of determination of 0.85 and a slope of 1.04. Thus using a crop factor approach will explain approximately 85 % of the variation in daily tree evaporation. The daily crop factor from March 2007 to December 2008 showed large daily variations; however applying a 30 day moving average reduced this variation to average values of 0.8 in winter and 1.3 in summer.

The groundwater levels monitored at four boreholes in the catchment responded to low winter rainfall by dropping approximately 5 m. There was a noticeable difference in the recharge with distance from the stream with those boreholes closer to the stream responding first to the wet season. The delay between the start of the recharge in the centre borehole and the western borehole (most delayed) was approximately one month in 2008. Based on the south borehole with the longest record, the dry season water level dropped from 35 m below surface in 2007 to 36 m in 2008. This was interpreted to be a result of the impact of the trees on groundwater recharge.

An accumulated ET_{LAS} versus accumulated rainfall graph showed that from August 2006 to December 2008 the total evaporation exceeded the rainfall by 46%. Deviations from the 1:1 line (step changes) were evident during the winters of 2007 and 2008. These significant changes in slope of the rainfall – ET_{LAS} curve were a direct result of the continued high transpiration rates from the trees combined with the low rainfall at these times.

The monthly water balance for the catchment was used to calculate the change in soil water storage. Measurements of volumetric water content to a depth of 2.4 m were compared with water balance estimates of changes in soil water storage. Losses unaccounted for were -671 mm over 17 months or approximately -40 mm month^{-1}. These deficits in the water balance could only be supplied from the deep soil water stores beyond 2.4 m. These data were evidence that the wattle trees (whose roots went deeper than 4.8 m) were able to access the deep groundwater reserves.

Both the WAVES- and ACRU-simulated soil water results were compared against measured values of soil profile water content to a depth of 2.4 m. The WAVES water content (561 mm) was very similar to the actual total profile water content (547 mm) whereas ACRU was noticeably different at 400 mm. During the simulation period, it was noticeable that the ACRU model values remained fairly constant throughout the year with only small responses to large rainfall events. By contrast, the WAVES model showed good agreement to the trends in the actual total profile water content. Generally the WAVES model tended to overestimate the response to summer rainfall events. Particularly good agreement was found between the measured and WAVES-simulated model values in the recession of the water content curves following large rainfall events. These data revealed that the WAVES values were within 20% of the actual values for 95% of the time while the ACRU model values were within the 20% range for only 5% of the time.

The streamflow simulations using ACRU showed that the accumulated streamflow over time was underestimated. During the period of measurement from January 2000 to December 2008 the measured accumulated streamflow was 400 mm. The simulated total streamflow using the “old” and the “new” ACRU versions were 300 mm and 275 mm respectively. The simulation followed the measured data closely until the end of 2004 when the catchment was clear-felled. From January 2005 to December 2008 the simulations appeared to consistently underestimate the streamflow and the Intermediate Zone ACRU more so than ACRU 3.31. This apparent divergence between simulated and observed data together with a change in the conditions of the catchment provided an excellent opportunity to verify model performance. It also showed that ACRU was not able to effectively simulate changes in streamflow from an afforested scenario to a fallow catchment.

6. Conclusions

In this study the impact of *A. mearnsii* on soil hydrological processes was extended with additional detailed measurements of evaporation and soil water processes to improve our understanding of processes such as low flows and deeper soil water dynamics. The ever-growing demand for water makes it imperative that water resource management procedures and policies be wisely implemented and improved. Recent studies have raised concerns over the impact of deep-rooted trees “mining” the soil water and groundwater reserves. The effect of excess evaporation over rainfall is ultimately transmitted into reductions in streamflow. Therefore, a better understanding of the hydrological processes of deep rooted trees is needed to improve the granting of licenses to water-users and for water allocation.

In this study we described the processes of supply (rainfall) and demand (climate and land-cover) for water and how they influenced the evaporation process. From a biophysical standpoint, a forest or plantation cannot in the long-term use more water through evaporation than is available from the input of rainfall minus runoff and infiltration of water below the root zone. To balance the water supply, plants can use a number of adaptive mechanisms (Baldocchi, 2007). On a short time scale plants can limit transpirational losses by closing stomata. In this study evidence of the *A. mearnsii* trees closing stomata on hot dry windy days was found. These extreme events are rare however, and not likely to influence the water balance on an annual basis. On a longer time scale (millennia) plants can develop morphological and ecological adaptations that can lead to reduced transpiration, such as leaf drop or developing smaller leaves to convect heat more efficiently. When considering an exotic plant like *A. mearnsii*, imported from Australia in the last century, then this is clearly not a consideration. In addition, this study has shown that the *A. mearnsii* trees at Two Streams transpire at rates that are close to the Priestley-Taylor potential rate of evaporation (i.e. there was no evidence of reduced transpiration). The most plausible adaptation of the *A. mearnsii* trees is the development of deep roots that can access alternative sources of water. The Two Streams catchment received a nine year average rainfall of 920 mm, with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm). The upper range may appear adequate, but not all will be available to the trees as there will be losses due to interception, surface runoff and deep percolation past the root system. In dry years the trees will have to resort to an alternative source of previously stored soil water. In this study the annual *ET* of the actively growing *A. mearnsii* was 1156 mm and 1171 mm and the rainfall 689 mm and 819 mm for 2007 and 2008 respectively.

Evaporation from the developing wattle plantation measured using a large aperture scintillometer was shown to exceed the rainfall by 46%, confirming the previous

Bowen ratio measurements (Jarmain and Everson, 2002). Potential evaporation rates estimated using the Priestley-Taylor equation were on average only 5% lower than to the ET_{LAS}. The implication of these results is that the wattle trees were using water at rates higher than the equilibrium rate throughout the year and that there was always some component of advective energy that increases the actual evapotranspiration. This means that true equilibrium potential evapotranspiration rarely occurred at the study site. Clearly, water was not a limiting factor to the wattle growth during its first three years of development.

Internationally, long-term catchment studies including actual measurements of all the water balance components are scarce; while locally this represents a unique study on the impact of an exotic tree plantation on catchment hydrological processes. The only other long-term data set to include actual measurements of *ET* was collected from the Cathedral Peak CVI in *Themeda triandra* dominated grassland in the KwaZulu-Natal Drakensberg (Everson *et al*., 1998). This study provided a baseline against which the impacts of commercial forestry and other land-uses could be assessed. The daily total evaporation (ET_{LAS}) values for the *A. mearnsii* trees on cloudless summer days averaged 7 mm. On clear winter days the maximum total evaporation was approximately 2.4 mm day^{-1}. This contrasts with the *Themeda triandra* grassland evaporation rates measured in the Drakensberg of 7 mm in summer and < 1 mm in winter (Everson *et al*., 1998). It is, therefore, the difference in the winter *ET* between grasses and evergreen trees that has the biggest impact on changing the catchment water balance. This will be particularly noticeable during the critical low flow (winter) periods.

The rainfall:runoff relationship (*Rr*) was 0.02 prior to clear-felling of the catchment in 2004. Following clear-felling the *Rr* increased to 0.08. This indicated increased runoff during the two-year fallow period and the first two years of wattle tree development. Forest management practices, therefore, have significant impacts on catchment water yields. The impact of clearing the riparian vegetation followed by clear-felling the entire catchment in 2004, a replanting in June 2006 and regrowth to January 2009, resulted in a total gain in streamflow of 235 mm.

In this study it was shown that the total input by precipitation was +1308 mm while the combined losses of *ET* and *Q* were -2120 mm. The measured change in soil water storage in the upper 2.4 m soil profile was -141 mm. Unaccounted for losses were therefore -671 mm or approximately -40 mm per month. These deficits in the water balance could only be supplied from soil water stores deeper than 2.4 m. These data are evidence that the wattle trees, whose roots went deeper than 4.8 m were able to access the deep groundwater reserves. Other evidence for supporting this conclusion included the following:

- The electrical resistivity survey and borehole logs confirmed the presence of deep clays with high water contents to depths of 25 m. This represents a significant soil water storage reserve for access by deep rooted trees.

- Dry season borehole data showed a drop in water level of 1000 mm between 2007 and 2008, despite more rainfall in 2008. This drop in level was ascribed to the impact of the trees on the recharge rate.

- The *A. mearnsii* roots were found at depths > 4.8 m.

- The measurements of soil water and soil water potential showed a consistent drying out of the deeper soil profile as the trees developed.

7. Extent to which contract objectives have been met

The objectives of the original project contract have been met as described below:

a. The first objective was to quantify the long-term effects of commercial forestry species on deep soil water profiles, streamflow and evaporation. Through detailed water balance studies this objective was achieved and the hydrological record for Two Streams extended by a further three years (objective four).
b. Objective two was to describe the controlling environmental and soil water processes which allow for total evaporation to exceed the annual rainfall. This was achieved by actual measurements of the catchment water balance which have contributed to a better understanding of these processes.
c. Objective three was to provide a modelling framework for the catchment water balance to improve stream flow predictions and specifically low flows. Nine years of detailed hydrological data provides an excellent data source for verification and development of hydrological models.

8. Capacity building and technology exchange

The Two Streams catchment is well recognised in forestry research in South Africa and has initiated collaboration between a number of research institutions. The University of KwaZulu-Natal use the catchment for student field trips and hydrological modelling and verification. University of the Free State pedology students gained experience in soil classification and mapping in the Two Streams catchment.

An Institute for Commercial Forestry Research field day used the Two Streams catchment as a showcase of forestry research in South Africa. In April 2008, The Department of Water Affairs and Forestry held a workshop titled, ‘International Workshop on Forest Governance and Decentralisation in Africa’. During the workshop approximately 60 national and international delegates attended a field trip to the study site.

A number of individuals benefited from this research:

Alistair Clulow was awarded his Masters degree (Agrometeorology) in 2008 based on the evaporation measurements performed during this project. He has worked extensively on the scintillometry component of this project and was exposed to other new techniques such as reference evaporation and TDR theory. He has also been involved in both workshops held in February and September 2006.

Dumisani Shezi from Zululand University participated in the installation of the instrumentation while studying a Masters degree (Agrometeorology) at the University of KwaZulu-Natal. He has subsequently accepted a post with The Department of Water Affairs and Forestry.

Lucas Ngidi, Lelethu Sinuka and Vivek Naiken from the CSIR have all been involved as technicians on the project. They have been exposed to new technologies and the complexities of instrumentation and site management.

9. Recommendations

The data collected and research infrastructure established in the catchment over the last nine years provides an excellent platform to extend the studies in the catchment and in particular to observe the changes in water-use and growth of the trees towards maturity.

The role of interception in the water balance is not well understood. This includes rainfall interception and mist interception which may be significant in this catchment as it is in a mist-belt area. Whether it is accounted for in the scintillometer measurements needs further investigation. A method of quantifying the mist and establishing its frequency requires further research.

Surface energy balance models using remote sensing techniques can provide estimates of plant water-use over wide areas but require validation for South African conditions. The state-of-the-art total evaporation measurements recorded at the site provide an excellent opportunity for testing these techniques in afforested catchments. These will, in the future, provide water resource managers with catchment-wide water-use estimates and assist researchers in monitoring the impacts and changes associated with global climate change.

Cylindrical TDR probes were designed for installation in deep soils and were installed to 4.8 m. Although the practical aspects of installing probes at deep depths were overcome, the data were noisy and could be improved by extending the wave guides. Soil water content measurements over the deep profile would help to quantify the unaccounted deficits estimated from the water balance equation. More detailed information on root growth, root distribution and root turnover would also benefit the understanding of the water-use of the trees.

Peak flows of 10 mm were recorded in January 2005 which coincided with the clear-felling of the catchment. Due to the exposed soil surface and impact of heavy machinery on the soil structure, significant amounts of topsoil were washed into the river and weir at this time. Based on the damage caused during these events, it is strongly recommended that tree harvesting in wet seasons in areas susceptible to erosion be evaluated with further research.

Over the past nine years, the impacts of different treatments to the riparian zone and upslope areas have been assessed. The interaction of the hydrological processes between these two areas (i.e. the interface) is still not well understood. In the catchment, the two zones are distinct from a vegetation, slope, soils and groundwater perspective and yet they interact within the hydrological cycle. For hydrological models to capture this interaction, further research into the transfer functions at the interface are required.

10. Data

All processed data have been stored at NRE, CSIR, Faculty of Agriculture, University of KwaZulu-Natal, Carbis Road, Pietermaritzburg, South Africa.

Contact persons: Mr. AD Clulow and Prof. CS Everson.

The data are backed up on tape by Metrofile and can be supplied as requested on CD-R diskettes.

11. Publications

Clulow A D, 2008. The long-term measurement of total evaporation over *Acacia mearnsii* using large aperture scintillometry, MSc. thesis, University of KwaZulu-Natal, South Africa.

Clulow A D, Everson C S, Gush M B, 2009. The estimation of total evaporation over acacia mearnsii using large aperture scintillometry. Poster presentation at 14th SANCIAHS Symposium, Pietermaritzburg, 21-23 September, 2009.

Everson C S, Clulow A D, Gush MB, 2009. The Long Term Impact of Acacia Mearnsii Trees on Total Evaporation, Streamflow and Soil Water Storage. 14th SANCIAHS Symposium. Pietermaritzburg, South Africa, 21-23 September 2009, pp 18.

1. INTRODUCTION

1.1 Background

The expanding human population has resulted in the need for increased food and timber production giving rise to increased competition for water between industries, municipalities and farmers. In addition, the scarcity of water is exacerbated by problems associated with water pollution and contamination, soil erosion, the invasion of alien vegetation and groundwater depletion. The implementation of a sustainable water resources management plan is required to meet these increasing demands on water resources. Evaporation is a significant component in the hydrological cycle and it is therefore critical that it can be understood and quantified (Savage *et al*., 2004).

For the purposes of quantifying water-use, the 1998 Republic of South Africa National Water Act refers to the volumetric determination of water for purposes of water allocation. In order to audit water-use in the natural environment it is important to consider how evaporation will be estimated as part of the hydrological cycle, especially from heterogeneous areas with exotic vegetation types that may have a high water-use.

The Two Streams catchment experiments have been used over the last nine years to study the impact of trees on hydrological processes (Everson *et al.*, 2008). The experiments provided a good opportunity for studies to extend our understanding of other processes such as low flows and deeper soil water dynamics. The Two Streams catchment is one of the few remaining small catchment research areas in South Africa. Streamflow gauging was started in 1999 in a mature stand of wattle trees (*Acacia mearnsii)*. Following a short calibration period, all the trees in the riparian zone were cleared in July 2000. The trees in the remainder of the catchment were removed in 2004/2005 and the catchment was replanted with wattle in August 2006. With nine years of intense hydrological monitoring, this catchment presented an ideal opportunity to study the impact of a newly planted *Acacia mearnsii* rotation on the water balance of the catchment and direct research towards previously unanswered questions.

Burger (1999), for example, estimated total evaporation (*ET*) using the Bowen ratio energy balance method and showed that annual total evaporation exceeded annual rainfall when measured over *A. mearnsii* at Two Streams during the exponential growth phase. This suggested that either the instruments used were providing incorrect results, or that tree roots were accessing groundwater and depleting soil water reserves from within the deep soil profile. Internationally, Baldocchi and Xu (2007) investigated the Mediterranean Oak (*Quercus douglasii*) for similar reasons. The trees were able to survive extended periods without water and total evaporation was also found to exceed rainfall.

The previous study (WRC K5/1284, Everson *et al*., 2008) showed that removing riparian wattle trees had a significant impact on increasing streamflow. This new phase of research had a focus on improving total evaporation measurements, understanding the monthly water balance and monitoring soil water storage in the deep soil profile in order to improve our understanding of the impact of perennial exotic trees on the catchment water balance.

1.2 Experimental Approach

Two approaches were adopted in this study:

1. Monitoring of rainfall, runoff, streamflow and deep soil water in an *A. mearnsii* plantation in order to calculate a monthly water balance for the catchment. The water balance was monitored from the initial planting stage in order to capture baseline measurements and establish the impact of the trees on the hydrological balance.

2. A modelling study to investigate the performance of the ACRU (Agricultural Research Catchment Unit) and WAVES (Water, Vegetation, Energy, Solute) models in estimating deep soil water fluctuations and seasonal responses.

1.3 Project Objectives

- quantify the long-term effects of commercial forestry species on deep soil water profiles, streamflow and evaporation;
- describe the controlling environmental and soil water processes which allow for total evaporation to exceed the annual rainfall;
- provide a modelling framework for the catchment water balance to improve stream flow predictions and specifically low flows; and
- extend the hydrological record for Two Streams to provide a long-term database of the catchment hydrological variables for future modelling studies.

1.4 History of Research and Funding at Two Streams

The original "Two Streams" project (funded by Working for Water), was planned for three years and was started in 1999 and ended in March 2002. This project was the focus of intensive research by the CSIR's hydrology group in Pietermaritzburg and the scale of the research expanded greatly in these first three years. The construction of gauging weirs, drilling of boreholes and instrumentation of the catchment took longer than originally anticipated. As a result, it became clear during the 2000 year that additional support would be needed in order gain maximum benefit from the funds already invested. Thus a second proposal to support this research and extend the measurements was submitted to the WRC and approved in April 2001. This funding extended the monitoring into early 2003.

Following a short calibration period, all the *A. mearnsii* trees in the riparian zone were cleared in July 2000. Eighteen months of data were collected to assess the impact of this clear-felling on runoff and hillslope hydrological processes. The plans to remove all the trees from the entire catchment in 2002 were delayed by technical problems experienced by Mondi with stripping bark and the trees were only finally felled from the catchment by December 2004. Although this allowed extended monitoring of the recovery of the riparian zone, it shortened the monitoring period of the cleared catchment. The continuation of the monitoring of the project in 2004 to 2005 and subsequent data analysis and write up in 2006 was therefore requested from Working for Water and the project was awarded an extension until 2006. These funds were transferred to the WRC who continued to manage the project.

By 2006, the Two Streams catchment had become one of the most intensely monitored forestry research catchments in South Africa, providing quantitative measurements of the impact of riparian management on the hydrology of the catchment. The funding for this three-year project was secured from the WRC in 2006, with the principal aim of investigating the impact of deep rooted trees on the catchment water balance.

2. THE STUDY AREA

The Two Streams catchment is situated 70 km from Pietermaritzburg near Seven Oaks on the Greytown road (Figure 2.1). The Bioregion is 'midlands mistbelt grassland'. The area is generally hilly with rolling landscapes and a high percentage of arable land. It is dominated by forb-rich, tall, sour *Themeda triandra* grasslands of which only a few patches remain due to invasion of native *Aristida junciformis.* Soil forms are apedal and plinthic and are derived mainly from the Ecca Group with dolerite dykes and sills. Rainfall is primarily in summer with an annual rainfall ranging from 659 to 1139 mm. Rain is most commonly from summer thunderstorms or cold fronts. Mist can be heavy and frequent and can add significantly to precipitation. Moderate frosts, droughts, hail and berg winds are also common to the area (Mucina and Rutherford, 2006).

Figure 2.1 The locality of the Seven Oaks district in the KwaZulu-Natal midlands.

2.1 Study site

Before the location of the study site was finalised, a preliminary stakeholder workshop was held in February 2006 at the Mistley-Canema Estate with a number of representatives from Mondi. Previous findings from research projects at Two Streams were presented and ideas proposed for the current project. Together with Mondi, a suitable forestry compartment was selected for the current work.

The compartment was considered suitable for the following reasons:

- it was in close proximity to instrumentation installed previously in the area allowing continued monitoring of old sites and comparison with the new sites,
- it was of a suitable size (6 Hectares) and had topography that complimented the use of scintillometry and
- it stood fallow for 2 years and was to be planted to Black Wattle (*Acacia mearnsii*) just after the commencement of the project, allowing baseline measurements to be made. In March 2006, the compartment was sprayed with herbicide and in June 2006 it was replanted with *Acacia mearnsii*.

The catchment details (boundaries, streams, roads, weirs, rain gauges, landuse, and monitoring sites) were mapped using a Trimble geographical positioning system, with accuracy better than 0.20 m and captured into Arc View GIS coverages (Figure 2.2). The position of the riparian zone had been delineated using the new riparian classification that delineates according to the presence of both a permanent and temporary water table (DWAF, undated). The Two Streams catchment was classified as a typical “B-stream”, where the contact of the water table and the stream is not permanent as in “C class” streams. A-zones were identified in the upper catchment where no water table existed.

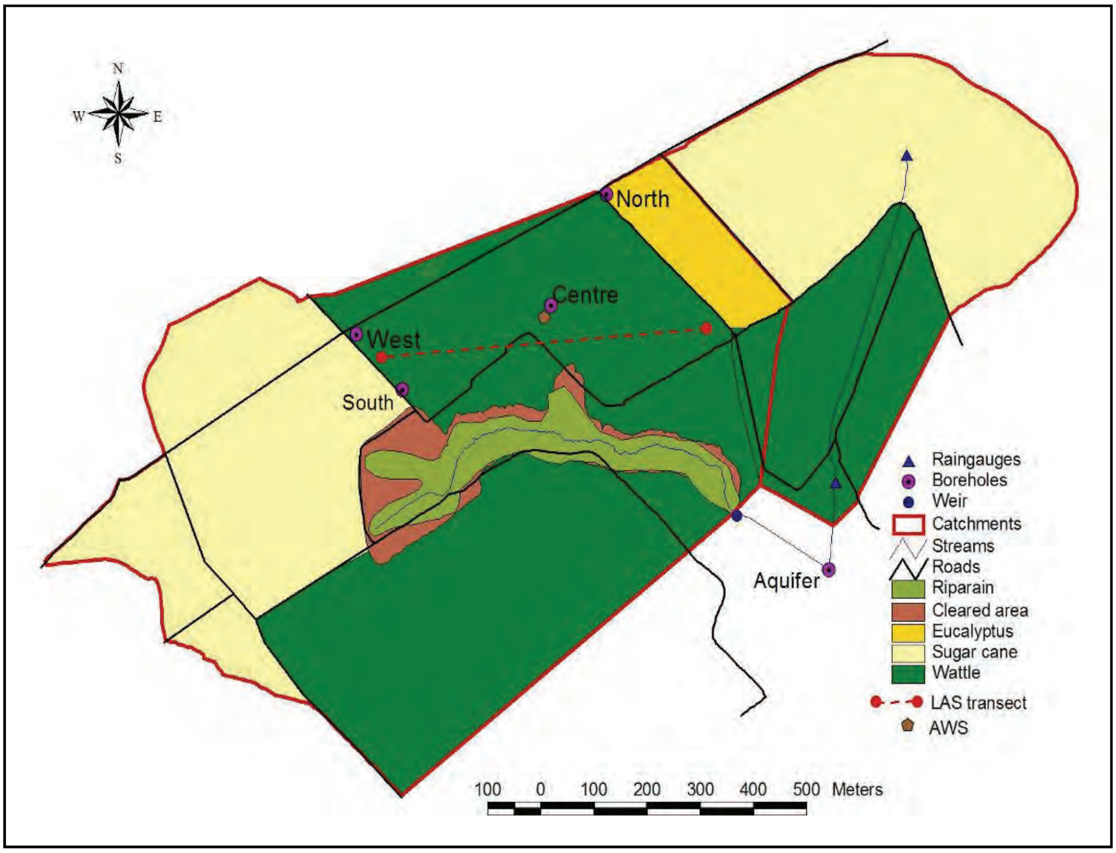


Figure 2.2. Location of the instruments in the Two Streams catchment. The large aperture scintillometer (LAS) transect is shown with the transmitter on the west and receiver on the east of the catchment. The AWS site included the area where the soil water measurements took place. The five borehole sites were labelled according to their position in the compartment.

3. MATERIALS AND METHODS

3.1 Tree Growth

Tree height is a critical measurement needed for the calculation of zero plane displacement, effective height and sensible heat flux from the LAS measurements and for understanding tree growth. Tree heights were sampled along the path length of the scintillometer at monthly intervals. Measurements were taken with a tree height rod of the same trees every month at 30 different sites, equally spaced on the LAS transect.

A LiCor LAI-2000 Plant Canopy Analyzer was used to measure Leaf Area Index (LAI) to give an indication of tree canopy growth. LAI is the surface area of leaf material per unit area of ground. Direct measurement of LAI is tedious and labour intensive but LiCor have developed an optical sensor connected to a control unit which enables easy estimation of LAI. Light readings made below the canopy are divided by readings made above the canopy to compute transmittances at five angles. A control unit records these readings and calculates LAI from the transmittances. There are a number of operating principals and limitations to the use of the LAI-2000 that should be noted. Sky conditions, sky brightness non-uniformity, field of view, canopy conditions and foliage size can cause error and need to be within the specification of the instrument (LAI-2000 Plant Canopy Analyzer, 1989).

Once the tree height increased beyond 2.0 m, two Plant Canopy Analyzers were required. One for below canopy measurements and the other to log above canopy light readings on the scaffolding above the trees. The data files were downloaded to a computer and LiCor software was used to merge the two files and calculate a LAI value at each of the 30 sites used along the transect.

Root samples were collected in February 2008 and again in February 2009 by auguring to depths of 4.8 m. These were passed through a 2 mm sieve using water and the remaining roots were air-dried and weighed. A representative root weight was calculated by dividing the weight of roots from a certain depth by the weight of the soil sample taken at that depth in order to obtain the mass of the roots (g) per kg of soil.

3.2 Rainfall

Rainfall was monitored at three sites in the catchment using tipping bucket raingauges (Figure 2.2). Two MCS-160 raingauges with a 0.2 mm resolution and one Texas Instruments raingauge with a 0.1 mm resolution were used. MCS raingauge 1 was located in the upper portion of the catchment while the lower raingauge 2 was situated close to the main weir. The third site was located in the plantation where the scintillometer was deployed. It was therefore possible to obtain an area weighted average of the rainfall records as input into the water balance calculations.

3.3 General Climatic Variables

Three Campbell Scientific automatic weather stations collected atmospheric data at Two Streams. The oldest station inherited from the previous Two Streams project (Figure 3.1) was located on a hilltop near the Mondi lookout tower and was maintained for data continuity and as a backup to the two newer stations. The second station was setup in a short grassland area to calculate the short grass reference evaporation according to the American Society of Civil Engineers-Environmental and Water Resources Institute (ASCE-EWRI) method (based on the Penman-Monteith method) (Figure 3.2). For further information on the ASCE method for determining the reference evaporation (ET_{sz}), refer to Allen *et al*. (2005) and Allen *et al*. (2006). The third AWS was sited at the centre of the scintillometer path on scaffolding above the canopy to provide additional data for the sensible heat flux calculations using the scintillometer (Figure 3.3).

The Penman-Monteith method is internationally recognised and popular for a number of reasons, including the relatively low data requirements and the relationship established between the reference and the total evaporation known as the crop factor (K_c) where $K_c = ET/ET_{sz}$. This relationship allows agronomists and hydrologists to estimate total evaporation from easily acquired standard weather station data. The LAS results of total evaporation were compared to the short grass reference standard for a period of 19 months and a crop factor for *A. mearnsii* calculated relative to the height of the trees.

The weather stations measured solar radiation, ambient air temperature, relative humidity, rainfall, wind speed and wind direction using Campbell Scientific Inc. (CS) data loggers (CR23X, CR1000 and CR21X). In addition, the AWS at the scintillometer site measured net radiation and soil heat flux using a Rebs Q-7.1 net radiometer, Rebs soil heat flux plates, CS soil temperature averaging probes and a CS616 soil water probe installed as in Figure 3.4. In the early stages of measurement when the trees were first planted, the wind speed measurements were at a height of 2 m. As the tree heights approached 2 m, the wind speed data showed a decline in average wind speed due to friction of the trees. Wind speed is critical in the calculation of the sensible heat from the LAS and a method of adjusting the wind speed was sought. The Log Wind Profile equation was used to estimate the wind speed at a higher level until the station was mounted on scaffolding (Rosenberg *et al.*, 1983). Thereafter a height of 2 m above the trees was maintained.

Figure 3.1. Original automatic weather station at Two Streams.

Figure 3.2. The automatic weather station near the Two Streams site established over short grass and used to calculate the short grass ASCE reference evaporation.

Figure 3.3. The above canopy automatic weather station in the centre of the wattle plantation used to collect net radiation and soil heat flux data as well as supporting meteorological data.

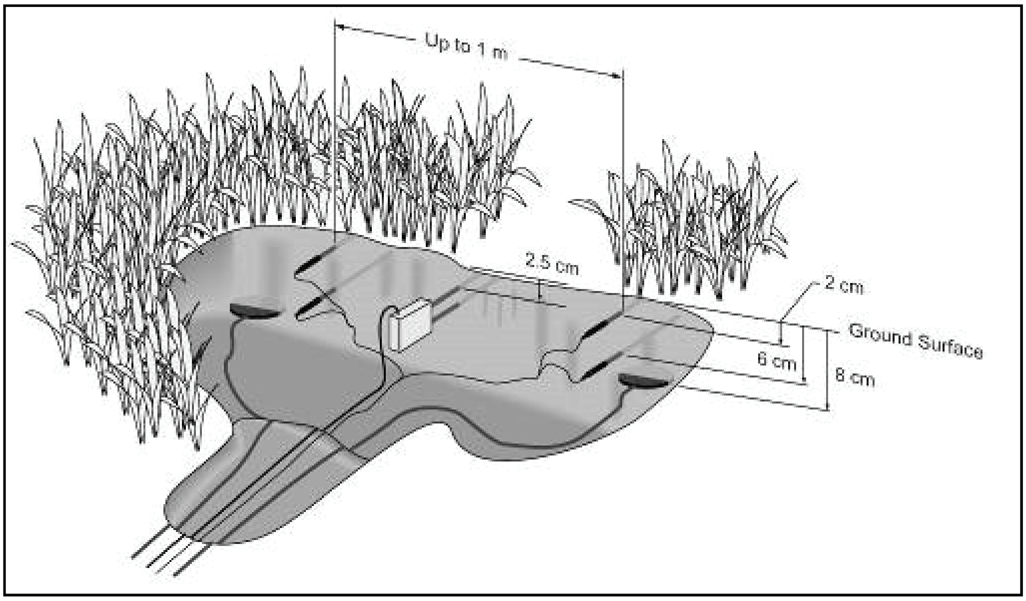


Figure 3.4. Layout of sensors used to estimate soil heat flux (after Campbell, 2003).

3.4 Evaporation Measurement Using Scintillometry

Scintillometry is a relatively new technique using electromagnetic scintillation to infer the surface fluxes of heat, moisture and momentum (Green, 2001). It offers the significant advantage of providing spatially-averaged evaporation estimates over distances up to 5 km; also being reliable and robust because of the absence of moving parts and relative simplicity of design. Additional advantages are that the instruments are highly portable, and that post-processing of data is uncomplicated.

Scintillometry has been used in a number of studies internationally to estimate total evaporation (Meijninger *et al*., 2006; Ezzahar *et al*., 2006) and exhibits a number of advantages over other methods such as Bowen ration and eddy covariance (Savage *et al*., 2004). The use of scintillometry has recently experience a renewed enthusiasm (de Bruin, 2002) and this document reports on its use over *A. mearnsii* at the Two Streams site. Although the theory of scintillometry does not account for advection, some studies have shown estimates from scintillometry affected by advection to be consistent and accurate (Hoedjes *et al*., 2002). The extended data set also allows for an initial assessment of the impact of advection at Two Streams.

The scintillation technique determines the path-averaged structure parameter of the refractive index of air (C_n^2) and is based on the propagation statistics of electromagnetic radiation through the turbulent atmosphere. When an electromagnetic beam of radiation propagates through the atmosphere, it is distorted by a number of processes that remove energy from the beam, leading to signal attenuation. The most dominant of these are small fluctuations in the refractive index of air caused by small temperature and humidity fluctuations. These refractive index fluctuations lead to signal intensity fluctuations that are known as scintillations. The system consists of a transmitter that beams a light source towards an accurately aligned receiver device.

The LAS used at Two Streams was made by Kipp and Zonen and was designed to measure the structure constant of the refractive index of air together with a few basic meteorological observations to estimate the sensible heat flux (F_h). The light source of the transmitter operates at a near-infrared wavelength of 880 nm. At this wavelength, the observed scintillations are caused primarily by turbulent temperature fluctuations. In this way, the scintillations measured by the receiver can be related to the sensible heat flux. The carrier beam is 7 kHz and the aperture diameter is 0.152 m. For further information on the theory of scintillometry, sensible heat flux and how the simplified energy balance equation is used to calculate total evaporation, refer to Clulow (2008).

Some of the particular advantages of the Kipp and Zonen LAS are:

- heated receiver and transmitter windows reduce condensation problems;
- a simple Fresnel lens construction avoids beam obstruction by a transmitting or receiving LED;
- on-board calibration allows rapid and on-site verification of accuracy;
- lightning and surge protection are standard on the transmitter and receiver;
- the infra-red light source is safe for eyes;
- 12 VDC power is required;
- alignment is simplified with pan and tilt adjusters.

At the Two Streams site, a suitable location was found with a path-length of 575 m with an east-west orientation. The block was fallow and about to be planted to *A. mearnsii* which suited the purpose of the project. The transmitter and receiver were initially mounted on a single level of scaffolding 3 m above the ground on 19 August 2006 (Figure 3.5). As the trees increased in height, the transmitter and receiver units were raised to an appropriate height (Figure 3.6). At the end of 2008 extra stages of scaffolding were used to raise the LAS receiver to a height of 18 m, while the transmitter was raised to 12 m above ground on a lattice mast. The LAS transmitter and receiver were mounted inside safe boxes with an opening on one side for the beam. The safe box provided protection from the elements and was also a theft deterrent. The scaffolding was stabilised on each side with supports (ledgers) and was also stayed with steel cables to prevent any movement of the tower. This was critical, particularly for the transmitter, as any movement would have an exaggerated affect on the beam alignment (transmitter mainly).

Power was supplied by four 100 Ah batteries requiring charging approximately every four weeks. A wind generator was used to augment the power, although this was not beneficial due to the generally low wind speeds experienced at the site. When the wind blew sufficiently to generate power, the voltage was raised, but not enough to extend the time between battery changes (Figure 3.7).

The power consumption of the transmitter increases with path length. For a transect of 575 m, the transmitter power consumption was approximately 0.125 A. The receiver consumption was approximately 0.25 A without the internal LAS lens heater connected. The heater draws an additional 1 A and was, for this reason, not connected at the site. The high power consumption of the heater units is unfortunate as heat on the lenses would have dried condensation or rainwater more quickly reducing the loss of data in the early morning. At remote sites where 220 VAC electricity is not available the use of the heaters is not practical due to limited battery power.

Alignment of the transmitter and receiver units requires precision and is an iterative process. Rifle scopes were mounted on each unit to assist. A signal strength meter at the back of the receiver gave an indication of alignment. The transmitter and receiver units were controlled by panning and tilting the units by an operator at either end until the maximum signal strength was obtained. Once the rifle scopes are sighted on well aligned scintillometers, they can be used very effectively to get the initial alignment at new sites.

Figure 3.5. *Initial installation height of LAS transmitter.*

Figure 3.6. *Scintillometer at a height of approximately 9 m.*

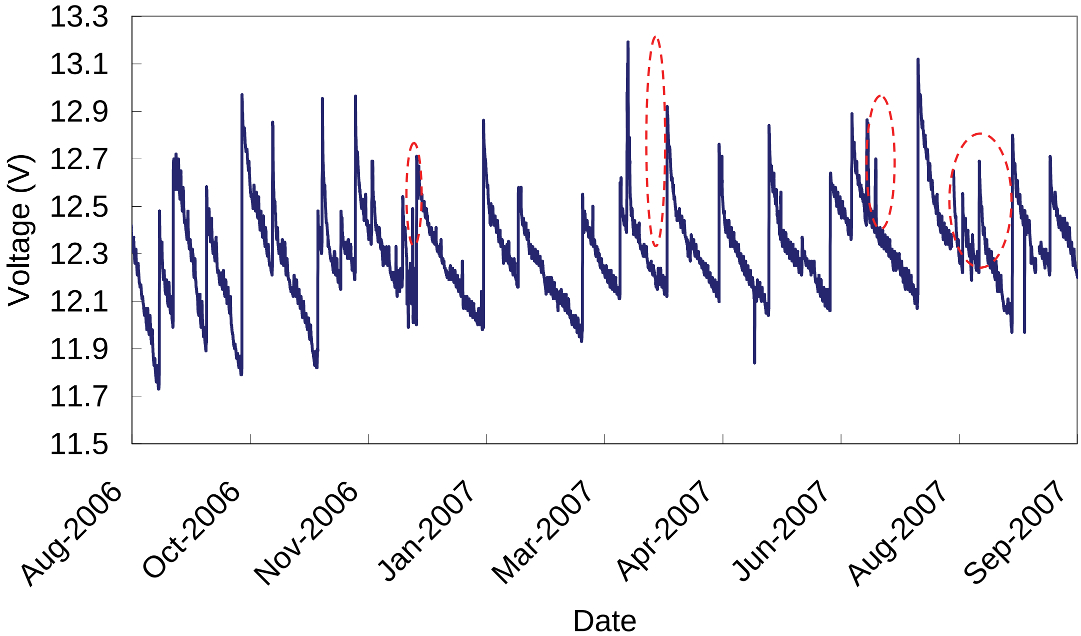


Figure 3.7. Battery voltage at the LAS receiver site. The impact of the wind generator is circled in red.

The signal strength on the transmitter and path length potentiometer on the receiver were set to appropriate values recommended in the user manual. A Campbell Scientific CR23X logger was used to log the data from the receiver LAS. The data were collected every 10 min and stored on the logger.

The calculation of sensible heat by the LAS software requires careful analysis of the height of the transmitted beam in relation to the tree canopy height (effective height) along the entire path length. In addition the calculation of zero plane displacement and friction velocity were calculated from the average canopy height. Refer to Meijninger (2002) and Clulow (2008) for definitions and calculations of these parameters. The ground surface profile was measured using a Trimble GPS, recording height and position coordinates between the transmitter and receiver. The canopy profile was obtained by adding the average canopy height measured along the LAS path to the ground surface profile. Figure 3.8 illustrates the variation in the canopy profile in relation to the beam path. Superimposed on Figure 3.8 is a bell-shaped function that illustrates the relative sensitivity of the beam to scintillations along the beam path. This variation in sensitivity follows a normal distribution and is well proven in many studies. This variable sensitivity along the path length is explained by an analysis of the geometry of light beams and the greater tendency by turbulent wind eddies near the centre of the beam path to diffract light in a way that causes rays to interfere destructively with each other, thereby causing scintillations. Figure 3.8 illustrates that scintillations over the Two Streams wattle plantation are most easily detected in the middle section of the beam path and hence more sensitive to fluxes in this area of the plantation. Due to the significance of the beam height above the tree canopy in the calculations of sensible heat flux, the calculations were performed at two weekly intervals and the LAS data were therefore processed at two-weekly intervals.

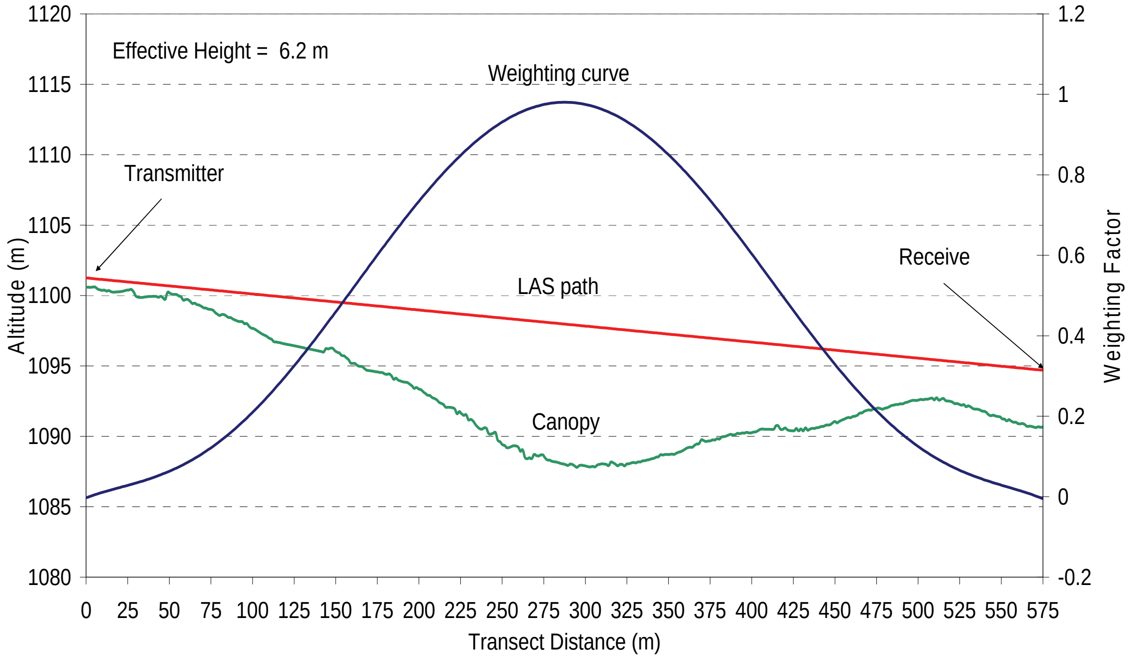


Figure 3.8. An illustration showing the height of the LAS beam in relation to the altitudinal profile of the ground as well as the sensitivity of the LAS to scintillations over the beam path (normalised weighting curve).

3.5 Computing Total Evaporation

Measurements from the soil heat flux plates, soil temperature averaging probes and volumetric soil water data were used to calculate the soil heat flux density (F_s). Values for soil bulk density, specific heat capacity of dry soil and specific heat capacity of water were estimated as 1000 kg m^{-3}, 837 J kg^{-1} K^{-1} and 4190 J kg^{-1} K^{-1}, respectively. The available energy was calculated by the difference between net radiation (R_n) and F_s.

Winlas software (Kipp and Zonen, 2007) was used to calculate the sensible heat flux from either: (1) the structure parameter of the refractive index of air (C_n^2), (2) the output signal from the receiver (U_{CN2}) together with the variance of U_{CN2}, or (3) scaled values of C_n^2 (P_{UCN2}) that have been multiplied by 10^{15} on the logger as most loggers cannot store the values of C_n^2 because they are too small.

For the Two Streams study P_{UCN2} was used, together with the horizontal wind speed, air temperature, air pressure and Bowen ratio. The software offers the user a number of options regarding ancillary inputs. Constant values of air temperature, relative humidity, air pressure and Bowen ratio can be used if data is not available, although some of these reduce the accuracy of the final results of F_h. If a constant value of windspeed is used then Winlas uses the free convection method to calculate the sensible heat flux. For this study, windspeed and temperature data were collected as these have a significant impact on the calculation of sensible heat (Meijninger *et al.*, 2000). The data were processed in two-week intervals due to the importance of capturing the changes in effective height, roughness length (z_o) and displacement height (d) of the trees over time.

A limitation of the LAS is that it does not provide the direction of the sensible heat flux. During the day when conditions are unstable, the flux is positive as there is heating of the atmosphere. At night when conditions are stable the flux is negative and there is cooling of the atmosphere. For the purpose of this study it was assumed to be positive while the net radiation was positive. This assumption was confirmed during a four-week period by mounting two fine wire thermocouples one above the other separated vertically by 2 m. The temperature difference showed a positive flux during the day and a negative flux at night with a transition period at dawn and dusk.

The Winlas output file includes a summary of the input data as well as the stable and unstable solutions of sensible heat flux, the free convection solution of sensible heat flux, the friction velocity and the Obukhov length. For the estimation of total evaporation from the LAS (ET_{LAS}), while the net radiation was positive the unstable solution of F_h was used and while it was negative zero evaporation was assumed. In reality it is not this simple and the sensible heat flux data required careful verification and checking, particularly in the early morning and late afternoon when there was a change from stable to unstable conditions or *vice versa*. Typically the first and last few values of F_h for a day were out of range and incorrect and were, therefore, excluded. In Figure 3.9, typical values for the unstable solution of F_h have been plotted while the net irradiance is positive. The values indicated by the dashed circles would have been omitted despite the net radiation being positive. Data requiring exclusion are easily identified as typically the sensible heat values are in excess of the net radiation for the first few 10 min readings in the morning. They then decrease to a minimum (usually < 5) from where they begin to climb and can be considered actual values of F_h. This transition period usually affected the data for about one hour in the morning and evening.

This verification process was performed using net radiation, air temperature, relative humidity and rainfall records to establish whether the elevated sensible heat flux values were real or transitional problems. These problems were usually associated with mist or rain and were reduced to zero. For this reason, the process of data collection involved: (1) removing all sensible heat flux data while net radiation was negative, (2) reducing all unrealistically high sensible heat values during the early morning and late afternoon conditions to zero, (3) excluding all latent energy values while sensible heat flux is zero.

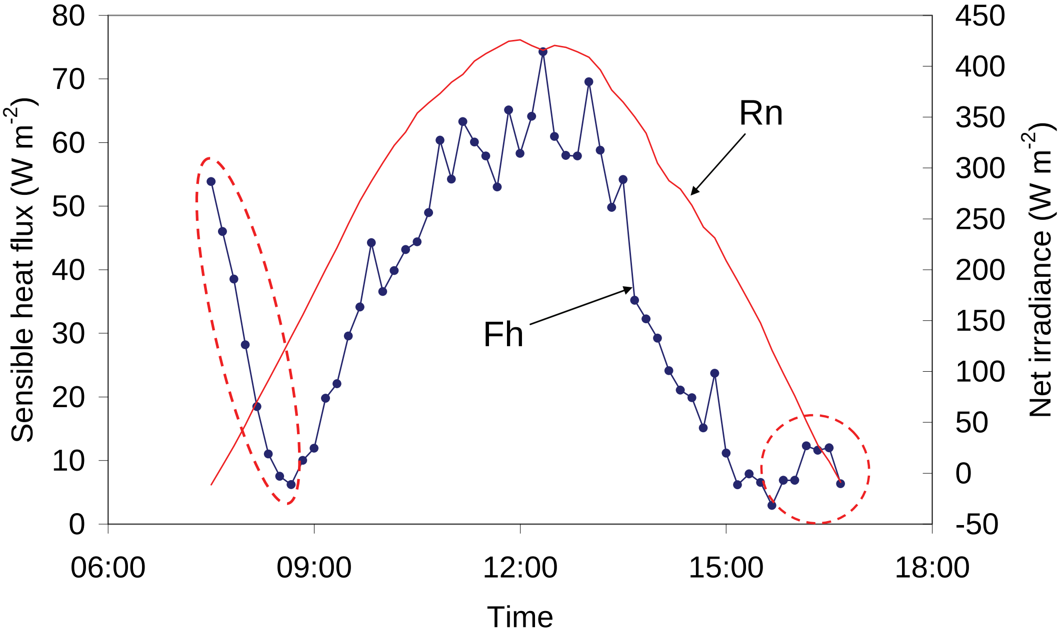


Figure 3.9. The diurnal variation in net irradiance (R_n) and sensible heat flux (F_h) for 20 July 2007 at Two Streams, showing that the early morning and late afternoon values of sensible heat flux required correction.

These problems associated with the stable-unstable transition periods occurred when total evaporation was low or insignificant and therefore have little impact on the daily totals. Much of the data in the results chapter are presented graphically and where required, trend lines have been plotted and a coefficient of determination calculated.

3.6 Streamflow

Catchment streamflow (*Q*) has been monitored continuously since 1999 using a 457.2 mm; 90° V-notch weir. A Belfort Streamflow recorder, modified with an MCS 250-01 streamflow encoder, was originally used and later replaced with an Ott Streamflow recorder and pressure transducer supplied by Department of Water Affairs and Forestry (DWAF). The calibration of the weir was carried out by DWAF staff and appropriate rating tables provided.

A sieve was installed in 2004 to avoid twigs and leaves getting trapped in the V-notch and affecting the level of the water in the weir (Figure 3.10).

Figure 3.10. A sieve in the main weir at Two Streams kept leaves and branches, which affect the level of the water in the weir, from getting trapped in the V-notch.

3.7 Electrical Resistivity Tomography Study

3.7.1 General description of resistivity method

The resistivity method is a non-invasive geophysical tool that can provide cost-effective answers to geological questions. Electrical resistivity contrasts generally exist between different geological units. During a resistivity survey electrical current is introduced into the subsurface and the potential difference between grounded electrode pairs is measured (Figure 3.11). From the ratio of the electrical current and measured potential difference, an apparent resistivity for the earth may be calculated. By using a different spacing for the current and potential electrodes, apparent resistivities are calculated for different depths of investigation (Figure 3.11). The apparent resistivities are then inverted by means of inversion algorithms to obtain information of the subsurface resistivity distribution. These inverted resistivity data may then be interpreted in terms of the geological conditions at the site under investigation.

Figure 3.11.   The cable and peg configuration used in the resistivity study.

3.7.2 Resistivity data collection and processing

Resistivity data were recorded at Two Streams in February 2007 along three traverses with approximate south-west/north-east strikes extending across the wattle site. The Global Positioning System (GPS) coordinates of the start and end positions of the three traverses are listed in Table 3.1, while the positions of the traverses relative to the wattle site are shown in Figure 3.12. The traverses were extended to positions laterally displaced from the wattle site in order to ensure that the resistive properties of the deeper earth materials underlying the wattle site could be measured along the entire length of the site.

Table 3.1. GPS coordinates for start and end positions of the resistivity traverses (projection: WGS 84, Lo29, accuracy ±5 m).

Traverse #	Start position		End position	
	X	Y	X	Y
1	160,217.8	-3,233,361.4	160,781.4	-3,233,034.2
2	160,172.1	-3,233,295.0	160,728.8	-3,232,988.1
3	160,121.3	-3,233,246.6	160,665.1	-3,232,905.6

The LUND imaging system, using Wenner geometry and a standard electrode spacing of 5 m, was used to record the resistivity data. All three traverses had the same length, namely 635 m. This length corresponds to a total number of 128 electrode positions along each traverse. Electrode spacings of 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 85 and 100 m were used during the survey in order to investigate the resistivity properties of the earth at different depths.

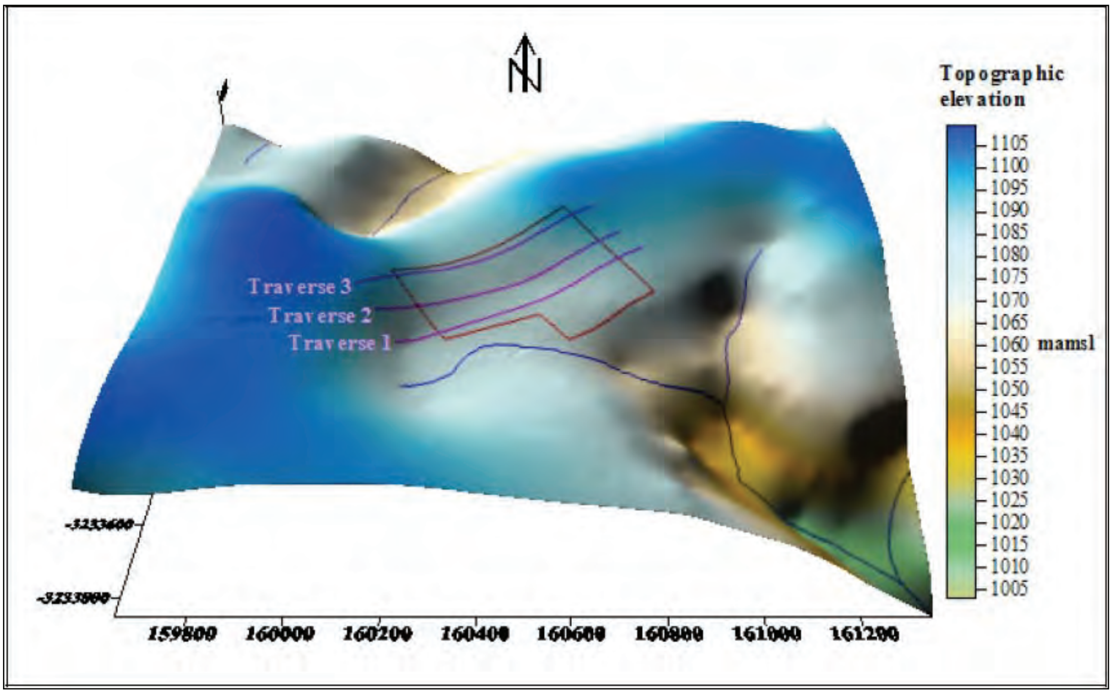


Figure 3.12. Position and orientation of the three resistivity traverses relative to the wattle site.

The apparent resistivity data recorded on the three traverses across the wattle site were examined to identify and remove erratic data that could affect the inversion routine. Topographic data from the 1:50 000 topographic sheet for the area were added to correct for lateral effects resulting from the changes in elevation along the profile. The resistivity data were then inverted by using the two-dimensional inversion software (RES2DINV).

3.8 Groundwater Monitoring

During the previous research project at Two Streams, DWAF drilled two deep boreholes (60 m+) at the upper and lower reaches of the catchment to monitor the deep aquifer. Depth to the bedrock varied between approximately 6 m near the stream to 14 m at the top of the slope.

During September 2007, DWAF made a further contribution to the project and drilled three more boreholes in the plantation. One borehole was drilled in the middle of the plantation, intersecting the scintillometer and the resistivity survey transects. The other two were drilled in the western and northern corners of the plantation. The central borehole was drilled to 40 m and the other two on the eastern and northern corners to 60 m.

Funds for automatic monitoring of the water levels in the boreholes were not available and the measurements were performed manually at monthly intervals.

3.9 Soil Water Dynamics

Previous work in the catchment has generated a database of nine years of detailed soil moisture data collected from tensiometers, watermark sensors and a neutron probe. This project required that the soil water measurements be refocused on deep profile water measurements with the design of a time domain reflectometry (TDR) probe that could be installed at depths in excess of 2 m.

3.9.1 Time domain reflectometry

In TDR methodology the travel time for a pulsed electromagnetic signal is measured. The travel time is dependent on the velocity of the signal and the length of the wave guide. The velocity is dependent on the dielectric constant of the material surrounding the waveguide. The dielectric constant of water relative to other soil constituents is high. Consequently, changes in volumetric water content can be related to changes in the dielectric constant of the soil material (Campbell Scientific TDR100 Instruction Manual, 2004).

3.9.2 Probe design

Issues investigated during the probe design process were probe length, configuration and the practicalities involved in probe insertion. The stainless steel probes have a length of 75 mm, a spacing of 15 mm and have a straight configuration (Figure 3.13). The probes were used with a Campbell Scientific TDR100 system with multiplexers allowing the installation and automated monitoring of more than 350 TDR probes from a single CR1000 logger. This has advantages over manual systems that require intensive, frequent site visits.

3.9.3 Sensor installation

A soil survey by the University of the Free State has shown the soils to be uniform in the plantation and hence a single study site for soil water in the centre of the plantation was chosen at which to monitor soil water dynamics. Initially, in February 2007, a pit to a depth of 2.5 m was excavated (Figure 3.14). Seven CS616 probes were installed as in Table 3.2 to a depth of 2.4 at 0.4 m intervals. This installation was necessary in order to start collecting soil water data while the new TDR probes (TDR_{CSIR}) were being designed and manufactured. They also served as a valuable validation for the data obtained from the TDR_{CSIR} probes. The process of probe design, manufacture and testing was completed and the TDR_{CSIR} probes were installed at the site in August 2007. These probes were installed using a soil auger with 1 m extension bars (Figure 3.15) to a depth of 4.8 m.

Later, in January 2008, watermark sensors were installed to a depth of 4.8 m, as in Table 3.2, in order to measure the matrix potential and allow for comparison with the volumetric water content results.

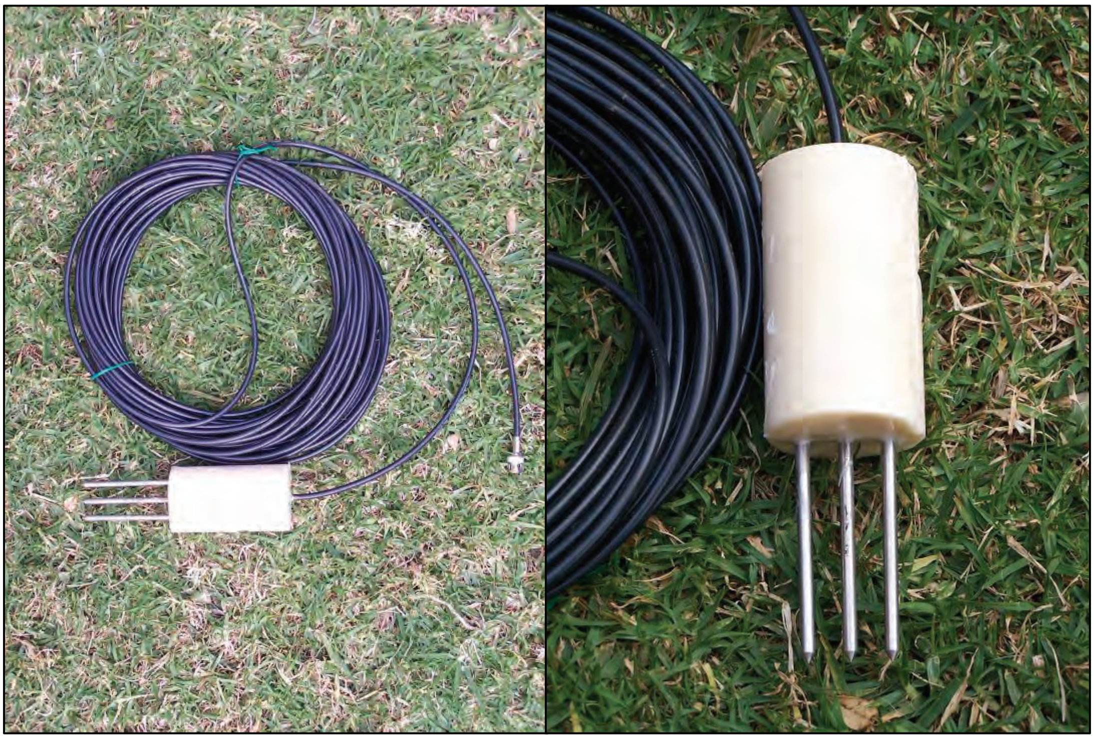


Figure 3.13. The design of the cylindrical TDR probes used for installation at depths > 2 m using an auger.

Figure 3.14. Pit excavated to a depth a 2.5 m at the centre of the scintillometer path at Two Streams for the installation of CS616 probes at 0.4 m intervals.

Table 3.2. The soil moisture sensor types and installation depths.

Depth (m)	Probe Type			
Surface	CS616			
0.4	CS616	Watermark	Cylindrical TDR	CS625
0.8	CS616			
1.2	CS616			
1.6	CS616	Watermark	Cylindrical TDR	
2.0	CS616			
2.4	CS616	Watermark	Cylindrical TDR	
2.8		Watermark	Cylindrical TDR	
3.2		Watermark	Cylindrical TDR	
3.6		Watermark	Cylindrical TDR	
4.0		Watermark	Cylindrical TDR	
4.4		Watermark	Cylindrical TDR	
4.8		Watermark	Cylindrical TDR	

3.9.4 Soil physical properties

During the excavation of the pit for the CS616 sensors, samples were taken in order to be able to convert matric potential results from the watermark sensors to volumetric water content for comparative purposes. Undisturbed soil cores were collected at 0.4 m intervals and were retained within a 50 mm x 75 mm stainless steel sleeve in order to measure water retention properties, bulk density and saturated hydraulic conductivity. Samples were collected in triplicate and, where possible, previous data was used to interpolate properties at specific depths. An equivalent set of disturbed samples were collected for measurement of particle size and organic carbon. The bulk density (ρ_b) and the mass water content of the sample (θ_m) at each matric potential were used to calculate the volumetric water content (θ_v) using the relationship $\theta_v = \theta_m \times \rho_b/\rho_w$ (where ρ_w = density of water). A full description of the methodology used can be found in Everson *et al.* (2008).

Figure 3.15. A soil auger with 1 m extensions was used to auger to a depth of 4.8 m.

3.9.5 Soil physical properties

During the excavation of the pit for the CS616 sensors, samples were taken in order to be able to convert matric potential results from the watermark sensors to volumetric water content for comparative purposes. Undisturbed soil cores were collected at 0.4 m intervals and were retained within a 50 mm x 75 mm stainless steel sleeve in order to measure water retention properties, bulk density and saturated hydraulic conductivity. Samples were collected in triplicate and, where possible, previous data was used to interpolate properties at specific depths. An equivalent set of disturbed samples were collected for measurement of particle size and organic carbon. The bulk density (ρ_b) and the mass water content of the sample (θ_m) at each matric potential were used to calculate the volumetric water content (θ_v) using the relationship $\theta_v = \theta_m \times \rho_b/\rho_w$ (where ρ_w = density of water). A full description of the methodology used can be found in Everson *et al.* (2008).

3.9.6 Soil survey

A soil survey in June 2007, led by Dr. P A le Roux of the University of the Free State together with a number of post graduate students, was conducted. The aim of the soil survey was to assist the students in gaining experience in performing soil mapping to document detailed profile descriptions of the transect of the north-facing and south-facing slopes, as well as the scintillometer plantation. The detailed soils information enhanced the hydrological modelling in the catchment.

3.10 Water Balance Modelling

A catchment water balance using the actual data was calculated at monthly intervals using:

$$P - Q - ET - \Delta S = 0$$

where, *P* is rainfall (mm), *Q* streamflow out of the catchment (mm), *ET* is total evaporation (mm) and ΔS is the change in soil water storage (mm).

3.11 Hydrological Modelling

Two models able to simulate deep soil water contents were configured for the catchment. The WAVES model (Water, Vegetation, Energy, Solute) is able to simulate soil properties to a depth of 4 m and ACRU (Agrohydrological Catchment Research Unit) is able to simulate a number of intermediate storage areas which can be defined by the user and hence, in theory, can simulate any soil depth. These models are significantly different in their purposes. ACRU is a catchment model with a focus on simulating streamflow from the catchment water balance; whereas WAVES is a one dimensional soil vegetation atmosphere transfer (SVAT) model. Both models, however, simulate similar components of the soil water balance and hence comparisons were possible. Soil profile water content was measured and used for comparing the models. Actual and modelled streamflow were also compared using ACRU. For the streamflow modelling, the standard ACRU 3.31 model and the new intermediate zone ACRU were used.

3.11.1 Description of the WAVES model

The WAVES model was considered to best meet the project requirements because of its ability to model to a depth of 4 m. It was developed by the Land and Water Co-operative Research Centre of the CSIRO in Canberra, Australia. It simulates energy, water, carbon and solute balances on a daily time step within a one-dimensional soil-plant-atmosphere system (Dawes and Short, 1993: Zhang *et al.*, 1996). It is well suited to investigations in soil water modelling and hydrological responses to changes in land management and climatic variation. The model is available free of charge from http://www.clw.csiro.au/products/waves/. A description from a comprehensive manual at the web site is available. It is also described by *Slavich et al.* (1998), Hatton *et al.* (1995), Zhang *et al.* (1996) and Zhang *et al.* (1999).

The primary strengths of WAVES are the following:

- It has the flexibility to be used on a wide range of plant functional types. This flexibility arises from:
  - Modelling two canopy layers (overstorey and understorey components) separately. This is particularly necessary for forests, woodlands and savannas.
  - Many physical differences displayed by vegetation types are explicitly taken into account. These include differences in albedo, aerodynamic resistance, canopy resistance, carbon allocation patterns, specific leaf area, light extinction coefficient, initial biomass and root carbon distribution with depth.
  - Annual crops may be simulated in the conventional way by specifying planting date, cumulative heat units to maturation and average shoot/root ratios.
- It simulates a wide range of factors limiting plant growth and water-use:
  - Soil water availability is the most important limitation to growth and water-use in South African vegetation, dryland crops and forest plantations. WAVES comprehensively models the daily water balance of a site, taking into account rainfall, canopy rainfall interception, overland flow and infiltration into the soil, redistribution within the soil profile, deep drainage below the rooting zone, evaporation from the soil surface, uptake by plant roots (overstorey and understorey) and transpiration from the plant canopies (one or two). The treatment of soil water dynamics is particularly detailed. The hydrological properties of soil texture classes are modelled according to the Broadbridge-White model and may be adjusted by running a subsidiary programme (BWSOIL.EXE). The influence of shallow water tables within the rooting zone may be simulated and is an important feature when modelling riparian vegetation. Slow declines in water table levels resulting from lateral drainage may be simulated.

- The effects of site aspect and slope on the interception of solar radiation by plant canopies is modelled. This is an important feature for simulations in areas of heterogeneous topography, since the interception of solar radiation is closely correlated to gross primary production. Solar radiation also governs net radiation at a site, which is an important controlling factor in the rate of evapotranspiration.
- The effects of solutes in soil solution and groundwater in limiting water uptake by plants may be explicitly modelled. Only the osmotic effect is taken into consideration. An important assumption in the model, however, is that chloride salts are assumed to occur. In situations where sulphate-dominated salts occur, such as in many sites influenced by acid mine drainage in South Africa, salinity effects may not be accurately modelled.
- The integrated rate methodology of Wu *et al*. (1994) is used to describe the effects of temperature, soil water availability and a soil fertility index in limiting plant growth on a given day. This index is flexible and additional limits such as the CO^2 concentration in the air may be added if required.

• WAVES is relatively simple by process-based model standards and lends itself to interfacing through user-friendly Windows screens to permit model use by non-specialists. Required weather input data are minimal. Daily maximum and minimum temperatures and daily rainfall are the minimum input requirements. If unavailable, the additional weather data required by WAVES (vapour pressure deficit and solar radiation) may be estimated from temperature and rainfall data using the well-known GENCLIM programme.

• Availability and support
  - The WAVES developers are available to offer support and advice.
  - A detailed and comprehensive manual is readily available on the Internet.

- The CSIRO are agreeable to making the FORTRAN source code available to serious users for enhancements to be made.
- Sets of parameter values for a range of crops, pasture and woodlands are available in the manual and in the WAVES literature.

In view of the excellent and very comprehensive electronic manual available on the WAVES website, only a brief overview of the model is provided here.

WAVES is a model of the soil-vegetation-atmosphere continuum which accounts for the major processes affecting vegetation growth and water-use. It may be briefly described by outlining the four principal modules. The energy balance module calculates net radiation from incoming solar radiation, air temperature and humidity and then partitions it into canopy and soil available energy using Beer's law. The water balance module handles surface runoff, soil infiltration, total evaporation (Penman-Monteith equation; Monteith, 1981), soil water redistribution (Richards equation; Richards, 1931), drainage and water table interactions. The model uses an efficient numerical solution to solve Richards' equation for unsaturated flow of soil water. The daily transpiration predicted by the Penman-Monteith equation is extracted from the profile using weighting factors determined by the modelled root density and a normalised weighted sum of the matric and osmotic soil water potential of each layer. The aerodynamic resistance of the plant canopy is assumed to be a constant value, while canopy resistance is calculated as a function of net assimilation rate, atmospheric water vapour pressure deficit (VPD) and CO_2 concentration. This is based on the empirical model of Ball *et al.* (1987) as modified by Leuning (1995). WAVES couples canopy and atmosphere using the omega approach described by Jarvis and McNaughton (1986). A particularly useful feature of WAVES is that it explicitly handles separate overstorey and understorey canopies that are a feature of forests, woodlands and savannas.

The carbon balance and plant growth module is based on calculating actual daily carbon assimilation from a maximum possible value and the relative availability of light, water and nutrients. The effects of temperature and salt in the soil solution are also simulated. The integrated rate methodology (IRM) of Wu *et al.* (1994) is used to combine the effects of the limiting factors into a single scalar. The actual carbon assimilated for a day is then dynamically allocated to leaves, stems and roots (Slavich *et al.*, 1998). The IRM scalar is also the basis for calculating canopy resistance, which is crucial to the estimation of daily transpiration obtained by solving the Penman-Monteith equation. Growth respiration rate is linearly related to the gross assimilation rate and maintenance respiration is linearly related to the mass of carbon and doubles for a 10° increase in average daily temperature. The rate of leaf, stem and root mortality is linearly related to the carbon mass of these components.

WAVES also includes a solute transport module that predicts solute transport within the soil column using convective dispersion equations and models the osmotic effect of salinity on water uptake by plants.

Daily inputs include day of year, maximum and minimum temperatures, mean vapour pressure deficit during daylight hours, total rainfall, rainfall duration and solar radiation. Additional and optional inputs are flood height, groundwater depth and grazing intensity. Examples of the set of parameters describing the plant attributes are provided in Figure 3.17. A large array of output values is provided, allowing a detailed picture of changes in daily site water balance and vegetation growth increment to be assessed.

WAVES has been thoroughly tested at experimental test sites in France and the USA (Zhang *et al.,* 1996), Australia (Salama *et al.*, 1999; Slavich *et al.*, 1998; Green *et al.*, 1997a and Green *et al.*, 1997b) and in China (Wang *et al.*, 1997). Test crops and vegetation types where the model has been successfully implemented have included grasslands, forests, mixed agricultural areas, *Eucalyptus* woodlands and a variety of different crops (e.g. wheat, oats, Lucerne, pastures).

3.11.1.1 Recent modifications to WAVES

Dye *et al.* (2008) performed a review of WAVES and identified areas of weakness if the model were to be used as a general model of vegetation/crop water-use by non-specialist users. They list the weaknesses as well as the actions that were taken to address the weaknesses. These include improving the user interface and adding a Wizard guide that assists the user in specifying the various inputs required by the user. In addition, a link to a climate database for South Africa was incorporated into the model in the form of a geographic information system (GIS) interface allowing a user to select stations closest to the point of interest.

3.11.1.2 Suitability for use at Two Streams

The WAVES model strengths regarding its application at Two Streams are:

- The ability of the model to accurately simulate complex vegetation types. The measured summer daily total evaporation rates have been as high as 9 mm and in winter 2 mm. This includes transpiration, soil water and intercepted water but the dominant component once the crop is established is transpiration. For this reason, it is important that the crop growth is simulated as accurately as possible. The vegetation parameter tab in WAVES requires numerous inputs allowing an accurate simulation of *A. mearnsii* trees that have been planted at the site.
- The model is able to deal with soil profiles to a depth of 4 m which will provide a good comparison with the deep soil water measurement at Two Streams.
- The hydrological properties of the soil textural classes are very detailed and the model is able to simulate interactions between the soil profile and the water table.

3.11.2 Description of the ACRU model

The ACRU model has its origins in a catchment evapotranspiration based study carried out in Natal in the early 1970s. The agrohydrological component of ACRU first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal. ACRU is a multipurpose model that integrates water budgeting and runoff components of the terrestrial hydrological system with risk analysis and can be applied in crop yield modelling, design hydrology, reservoir yield simulation and irrigation water demand/supply, regional water resources assessment, planning optimum water resource allocation and utilisation, climate change, land-use and management impacts and resolving conflicting demands on water resources. The ACRU model uses daily multilayer soil water budgeting and has been developed essentially into a versatile total evaporation model (Schulze, 1995). It has therefore been structured to be highly sensitive to climate and to land-cover/use changes on the soil water and runoff regimes, and its water budget is responsive to supplementary watering by irrigation, to changes in tillage practices, or to the onset and degree of plant stress. The model requires fundamental input data comprising daily rainfall and other climate data, as well as soils and natural land cover data for the site under investigation. Input to the menu is controlled by a "menubuilder" program where the user enters parameter or catchment-related values or uses defaults provided. The model revolves around multi-layer soil water budgeting (Figure 3.16).

Streamflow is generated as stormflow and baseflow, depending on the magnitude of daily rainfall in relation to dynamic soil water budgeting. Spatial variation of rainfall, soils and land cover is facilitated by operating the model in "distributed" mode, in which case the catchment is sub-divided into sub-catchments. These sub-catchments facilitate simulation of land-use changes, or isolation of riparian zones, through the designation of units of similar hydrological response, based largely on land-use zones.

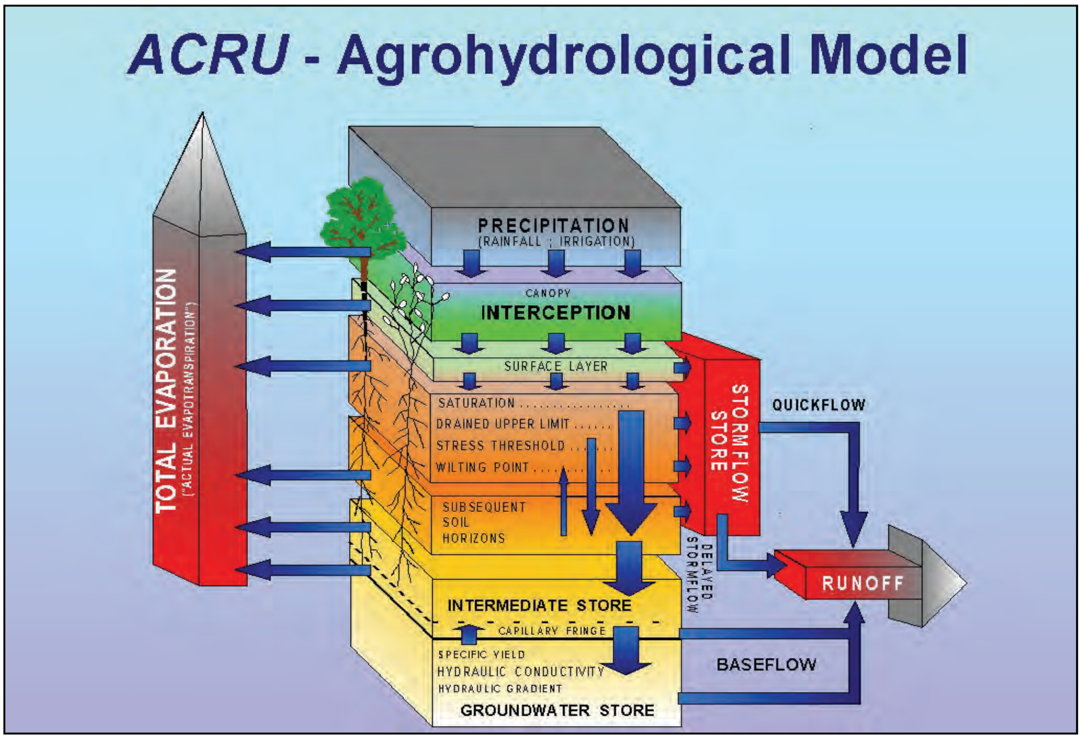


Figure 3.16. A conceptualised illustration of the ACRU model (after Schulze, 1995).

The original DOS-based version of ACRU has been replaced by the Windows-based ACRU 2000. More recently, an Intermediate Zone ACRU has been developed through funding by the Water Research Commission in a project titled, 'An Investigation and formulation of Methods and Guidelines for the Licensing of SFRA's with Particular Reference to Low Flows'. In this study, the shortcomings of ACRU were identified and the following modifications were made:

Inclusion of the Penman-Monteith equation, parameterised (according to the Granier Lohammer formulation) to take account of:

- atmospheric saturation deficit;
- soil moisture stress;
- low resistances of wet canopies;
- Hillslope hydrological processes as conceptualised and parameterised by Lorentz and co-workers, including:
    - flow generation based on a hillslope section contributing areas

- time distributed arrival of subsurface water based on hillslope criteria;
- an additional soil layer underlain by a relatively impermeable layer, allowing lateral discharge under “perched water table conditions”; and
- option of layer connection mechanisms

3.11.2.1 Suitability for use at Two Streams

Of particular relevance are the recent developments to the model relating to soil water processes. The model is able to simulate an intermediate zone with lateral discharge due to a perched water table and the connection mechanisms between the soil profile layers can now be defined by the user. The capabilities of the model to simulate an intermediate store and the interactions between the intermediate store and the groundwater store are beneficial and will be investigated further in this project.

The total evaporation routines have recently been updated and the model has been used for the simulation of stream flow reduction activities. It is therefore beneficial to continue this work and assess the progress made with ACRU by making comparisons between the modelled results and the measured data collected in this study.

3.11.3 WAVES catchment configuration

3.11.3.1 Climatic data

The WAVES model requires maximum and minimum air temperature, solar radiation and rainfall, all at a daily interval as climatic input. This was all obtained in the same way as described for the ACRU model.

3.11.3.2 Soils information

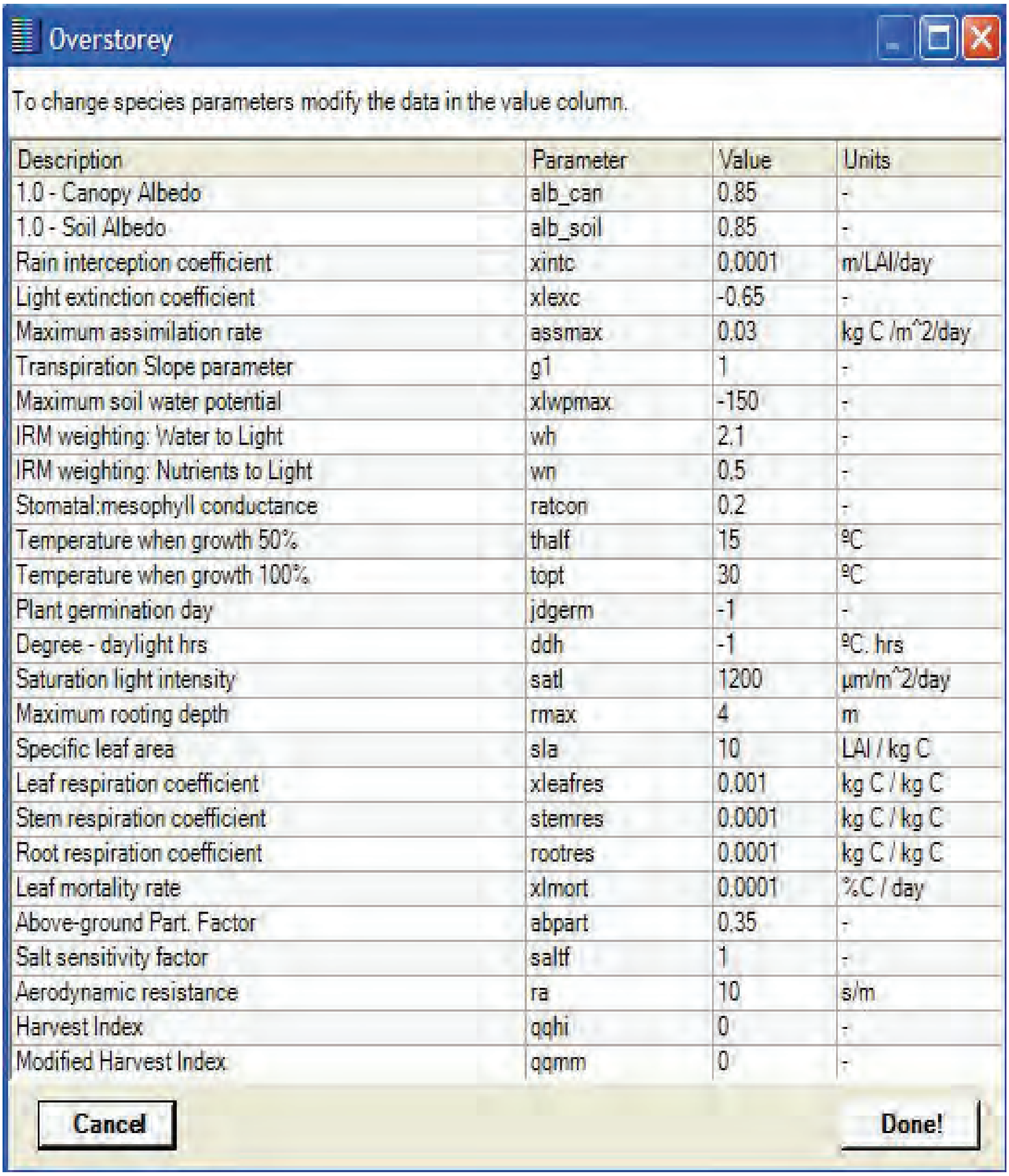
Soil samples were collected to a depth of 4.0 m at 0.4 m intervals and analysed in a laboratory for soil textural class. From this information WAVES assumes values of wilting point, drained upper limit and saturation. At each depth interval however (referred to as soil nodes in WAVES), the initial water potential, soil texture, salt concentration and root carbon can be selected individually. The soil textural class was critical in this study as soil profile water content was used as a verification of the model performance.

3.11.3.3 Land-cover and model setup

The model was run from 1 January 2006 to 31 December 2008 allowing the simulation of the 6 ha *A. mearnsii* crop from planting to a height of approximately 9 m on average at the end of 2008. The WAVES model has numerous inputs for vegetation parameters (Figure 3.17). Values for *A. mearnsii* were measured or estimated from similar trees.

3.11.4 ACRU catchment configuration

The catchment is the area upstream of the weir and is just 0.73 km^2 in size. For the purposes of this simulation, it was sub-divided into two sub-catchments consisting of a 0.08 km^2 riparian zone and 0.65 km^2 being the remainder of the catchment (Figure 3.18). The position of the riparian zone was delineated using the new riparian classification that delineates according to the presence of both a permanent and temporary water table (DWAF, undated).



Overstorey

To change species parameters modify the data in the value column.

Description	Parameter	Value	Units
1.0 - Canopy Albedo	alb_can	0.85	-
1.0 - Soil Albedo	alb_soil	0.85	-
Rain interception coefficient	xintc	0.0001	m/LAI/day
Light extinction coefficient	xlexc	-0.65	-
Maximum assimilation rate	assmax	0.03	kg C /m^2/day
Transpiration Slope parameter	g1	1	-
Maximum soil water potential	xlwpmax	-150	-
IRM weighting: Water to Light	wh	2.1	-
IRM weighting: Nutrients to Light	wn	0.5	-
Stomatal:mesophyll conductance	ratcon	0.2	-
Temperature when growth 50%	thalf	15	ºC
Temperature when growth 100%	topt	30	ºC
Plant germination day	jdgerm	-1	-
Degree - daylight hrs	ddh	-1	ºC. hrs
Saturation light intensity	satl	1200	µm/m^2/day
Maximum rooting depth	rmax	4	m
Specific leaf area	sla	10	LAI / kg C
Leaf respiration coefficient	xleafres	0.001	kg C / kg C
Stem respiration coefficient	stemres	0.0001	kg C / kg C
Root respiration coefficient	rootres	0.0001	kg C / kg C
Leaf mortality rate	xlmort	0.0001	%C / day
Above-ground Part. Factor	abpart	0.35	-
Salt sensitivity factor	saltf	1	-
Aerodynamic resistance	ra	10	s/m
Harvest Index	qqhi	0	-
Modified Harvest Index	qqmm	0	-

Cancel Done!

Figure 3.17. User entered inputs describing the vegetation cover modelled in WAVES.

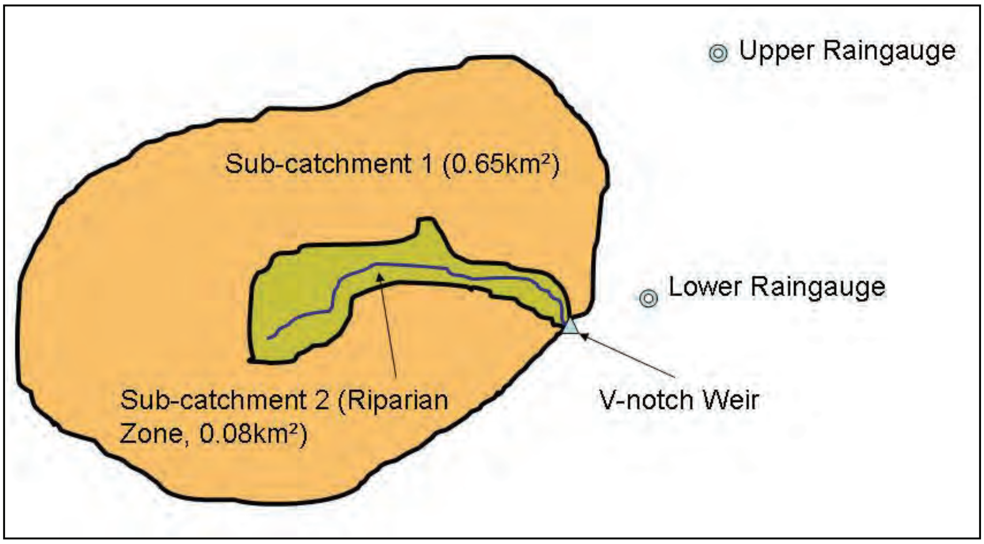


Figure 3.18. Simplified layout of the Two Streams catchment, showing sub-catchment configuration and position of gauging instruments.

3.11.4.1 Rainfall and streamflow data

Rainfall was monitored at two sites in the vicinity of the catchment (Figure 2) using tipping bucket raingauges (MCS-160) with a 0.2 mm resolution. Gauging sites consisted of an upper site at an altitude equivalent to the top of the catchment and a lower site at a similar altitude to the weir. These gauges facilitated the collection of rainfall data across the altitude gradient of the study area. In general, there was good correlation between the upper and lower gauges. The long-term mean annual precipitation (MAP) for the area is 853 mm (Lynch and Schulze, 2006); however the MAP for the monitoring period 1999 to 2008 was 901 mm. The annual rainfall for the first hydrological period of study (October 1999 to September 2000) was 1071 mm. This compares with 897, 1170, 659, 727, 1139, 1106, 689 and 819 mm for the 2000/2001 to 2007/2008 seasons respectively.

Streamflow was monitored continuously in the catchment using a 457.2 mm; 90° V-notch weir with a Belfort Streamflow recorder modified with an MCS 250-01 streamflow encoder. This was later replaced, after theft of the original instruments, with an Ott Streamflow recorder and pressure transducer supplied by DWAF. The calibration of the weir was carried out by DWAF staff and appropriate rating tables were provided, which were used to transform minute by minute readings of stage height into daily streamflow values (m^3 day^{-1} and mm).

3.11.4.2 Additional climatic data

A Campbell Scientific automatic weather station, located on the Mondi estate was used to measure ambient temperature, relative humidity, rainfall, solar radiation and windspeed at hourly intervals during the study. Periods of missing data were supplemented with data from a SASRI automatic weather station situated at Wartburg (http://www.sasa.org.za/sasri/). All data were collated into daily and monthly totals or means and are summarised in Table 3.3.

Table 3.3 Monthly means of daily climatic data for Two Streams.

Month/ Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T-Max (°C)	26.2	26.6	26.6	24.8	22.8	21.0	20.3	21.1	22.4	23.4	24.3	25.5
T-Min (°C)	16.1	16.3	15.4	13.4	10.4	8.3	7.9	8.8	10.1	12.0	13.3	14.8
Rel. Hum. (%)	81.5	81.4	79.5	75.8	64.5	63.0	62.7	64.1	66.9	72.7	76.3	77.4
Solar Rad. ($MJ.m^{-2}.day^{-1}$)	19.3	18.1	16.3	13.7	12.3	11.5	12.5	13.9	15.7	16.5	17.3	18.8
Windrun ($km.day^{-1}$)	184	159	152	140	149	156	180	199	227	216	223	202
A-pan equiv. ($mm.day^{-1}$)	5.0	4.7	4.3	3.6	3.2	3.1	3.4	3.8	4.0	4.8	4.8	5.1

3.11.4.3 Soils information

The soil characteristics at Seven Oaks were determined by means of a GIS plantation boundary overlay on the Institute of Soil Climate and Water (ISCW) (1993) land type maps using the Autosoils technique derived by Pike and Schulze (1995).

3.11.4.4 Land-cover and model setup

The simulation was run from 28 January 2000 to 31 December 2008. As land cover in the catchment changed significantly at various stages during this period, it was necessary to simulate those periods individually using input parameters relevant to the land cover at the time. Although there were some areas in the catchment under sugar-cane, the majority of the catchment was under *A. mearnsii*, and the most significant land cover changes involved this species. Consequently, three individual simulations were carried out and the results were appended to each other to mimic significant actual changes in land cover. Use of a “dynamic file” to represent temporal changes in land cover as they occurred was not possible in the versions of ACRU used for this exercise, but would have facilitated a more realistic representation of actual land cover variations over time.

4. RESULTS AND DISCUSSION

This project has provided the opportunity to collate and document historic results together with recent data. Although the historic data is included in the results, it is discussed where it impacts on the interpretation of recent results. Further information on previous results can be found in Everson *et al*. (2008).

4.1 Tree Growth

The management of the plantation and catchment area was facilitated by Mondi Forestry. After the initial planting in June 2006, blanking was required in August due to an approximate 20% fatality rate. This resulted in trees at two slightly different stages of development; however this difference rapidly became insignificant. Prior to planting, the plantation was sprayed in March with herbicide. During planting, dead plant material and weed re-growth were manually cleared from the rows and left as mulch in the inter-row (Figure 4.1). In October 2007, the inter-rows were sprayed with herbicide to control the weeds and reduce competition using a very effective method which only applied herbicide to the inter-row weeds (Figure 4.2).

4.1.1 Tree height

The consistency of the tree height growth curve showed that tree growth was not noticeably affected by seasonal fluctuations (Figure 4.3). This indicated that climatic variables such as rainfall, air temperature and radiation do not appear to limit tree growth significantly at Two Streams. During the first 2.5 years, the average tree height growth rate was 0.37 m per month or 4.5 m per year. This growth rate is expected to slow down significantly based on the levelling out of the tree height growth curve in Figure 4.3 over the last three months despite the onset of summer.

Figure 4.1. Black Wattle (Acacia mearnsii) planted in June 2006 after lying fallow for two years.

Figure 4.2. Spraying herbicide onto the inter-row areas without affecting the trees by using a portable spraying booth connected to backpack sprayers.

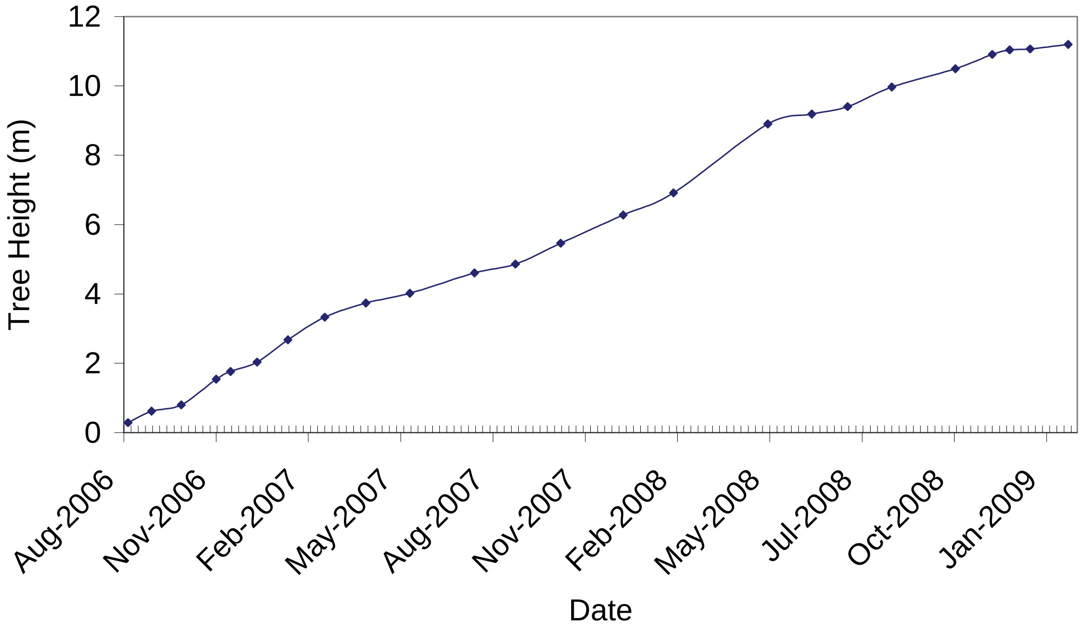


Figure 4.3. Tree heights of A. mearnsii *measured at Two Streams from August 2006 to August 2008.*

4.1.2 Leaf area index (LAI)

The LAI fluctuated initially due to tall, dense weeds during the summer of 2006/2007 when weeds grew vigorously but died off in winter 2007 (Figure 4.4). The influence of weeds was less significant in the following summer of 2007/2008 as the canopy developed and the individual rows became indiscernible (Figures 4.5, 4.6 and 4.7).

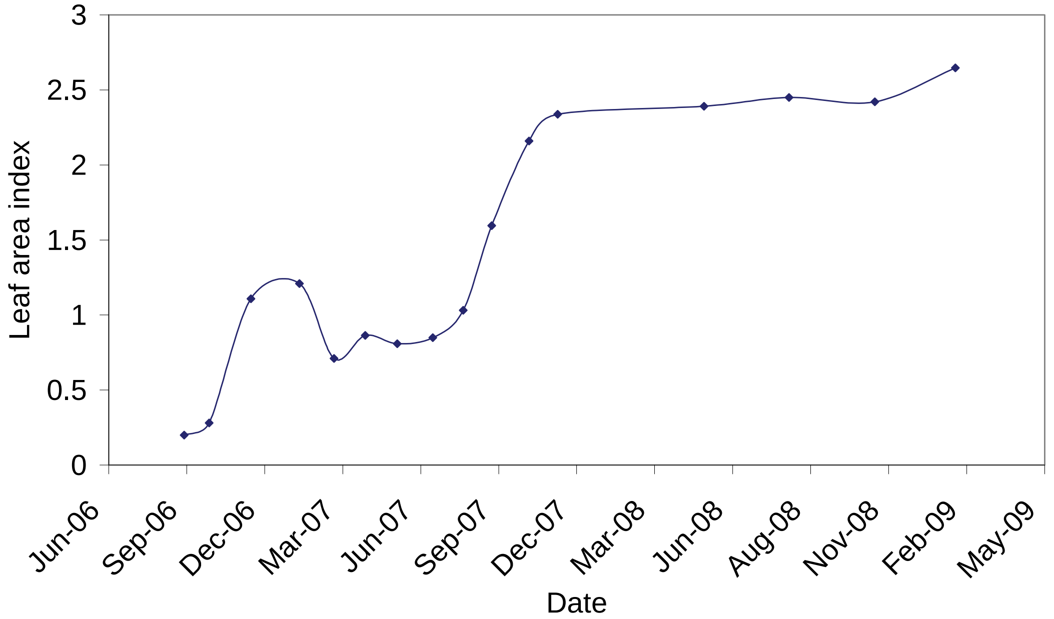


Figure 4.4. LAI measurements at Two Streams from August 2006 to May 2008.

Figure 4.5. A view across the site at Two Stream, from the transmitter on 3 m scaffolding towards the receiver in August 2006.

Figure 4.6. A view across the site at Two Streams; from the transmitter on 6 m scaffolding towards the receiver in August 2007.

Figure 4.7. A view across the site at Two Streams; from the transmitter on a 12 m lattice mast towards the receiver in August 2008.

4.1.3 Roots

Excavation of the soil water probe pits provided an ideal opportunity to determine the initial root distribution in the soil profile. Within the open face of the soil pit, a 1 m wide section was cut smooth with a spade and divided into 0.4 m intervals. Individual roots exposed at the cleared face were carefully counted revealing the following distribution (Table 4.1).

The following should be noted:

- for practical reasons the top 60 mm of soil was not included in the data but contains a high density of fine roots and organic matter;
- root diameters < 0.5 mm were classified as fine and those > 0.5 mm as large;
- prior to canopy closure in the summer of 2007/2008 there were a large number of annual weeds in the inter-rows. The data in the upper layers would have contained some of these roots.

A high proportion of fine roots occurred in the top 1.2 m of the soil profile although some fine roots were still found at 2.4 m. The few large roots were limited to the upper 1.6 m of the soil profile.

Table 4.1. Distribution of roots on 1 February 2007 in the excavation pit.

Depth (m)	Large roots (> 0.5mm)	Fine roots (< 0.5mm)
0.06-0.4	15	189
0.4-0.8	14	135
0.8-1.2	9	120
1.2-1.6	4	51
1.6-2.0	0	16
2.0-2.4	0	2

The distribution of root mass over the profile for the two consecutive years showed a similar pattern with a high root mass near the surface, a reduction towards a depth of 2 m, followed by a noticeable increase in root mass at 3.2 m (Figure 4.8). There were however significant differences in the 2008 and 2009 data. The root mass at 0.4 m dropped from 0.02 to 0.011 g kg^{-1} as a result of canopy closure and a reduction in the weed root mass in 2009. From a depth of 0.8 m to 4 m the pattern is similar for both samples but the 2009 root mass is greater than the 2008 root mass particularly at depths of 2 m and 3.2 m as a result of the wattle trees extending their roots to deeper depths.

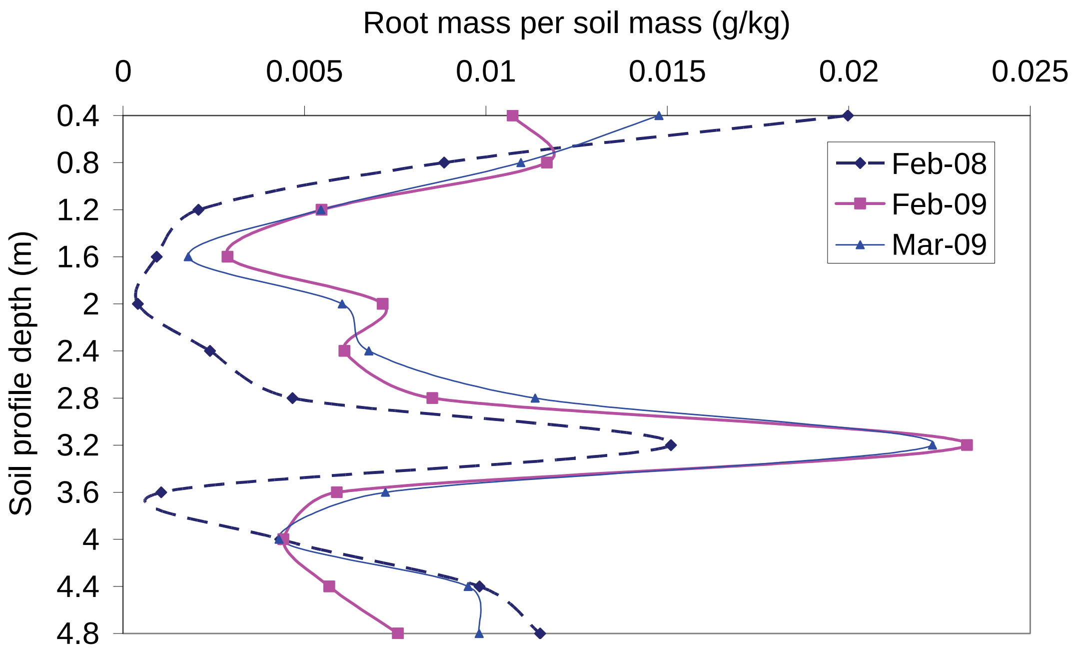


Figure 4.8. The root mass (g kg-1 of soil) found at Two Streams in February 2008 and 2009.

4.2 Rainfall Monitoring

The Two Streams research catchment lies in the summer rainfall zone of South Africa, where summers are wet and humid and the winters are dry and cold. Daily and monthly rainfall totals exhibited typical seasonal trends, with wet summer and dry winter periods (Figures 4.9 and 4.10). The long-term mean annual precipitation for the area is 853 mm (Lynch and Schulze, 2006), however the MAP for the monitoring period using the two long-term rain gauges in the catchment 1999 to 2008 was 920 mm. The annual rainfall for the first hydrological period of study (October 1999 to September 2000) was 1071 mm. This compares with 897, 1170, 659, 727, 1139, 1106, 689 and 819 mm for the 2000/2001 to 2007/2008 seasons respectively. Annual rainfall at the study site was therefore highly variable with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm).

The nine-year study period was characterized by an initial three-year period of normal to wet conditions, while the 2002/2004 period was dry, reflecting the severe drought conditions experienced in KwaZulu-Natal in the 2003/2004 season. The daily distribution of rainfall (Figure 4.9) reflected these dry conditions and only a few rainfall events of over 30 mm were recorded. By contrast the 2004/2005 data showed that the rain events between July and December 2004 were higher than any previously measured rain events for the study period and the highest single rainfall event during this study was measured on 19 November 2004 when over 90 mm of rain fell. The 2006/2007 data once again showed a dry period caused primarily by uncharacteristically dry weather in February and March of 2007.

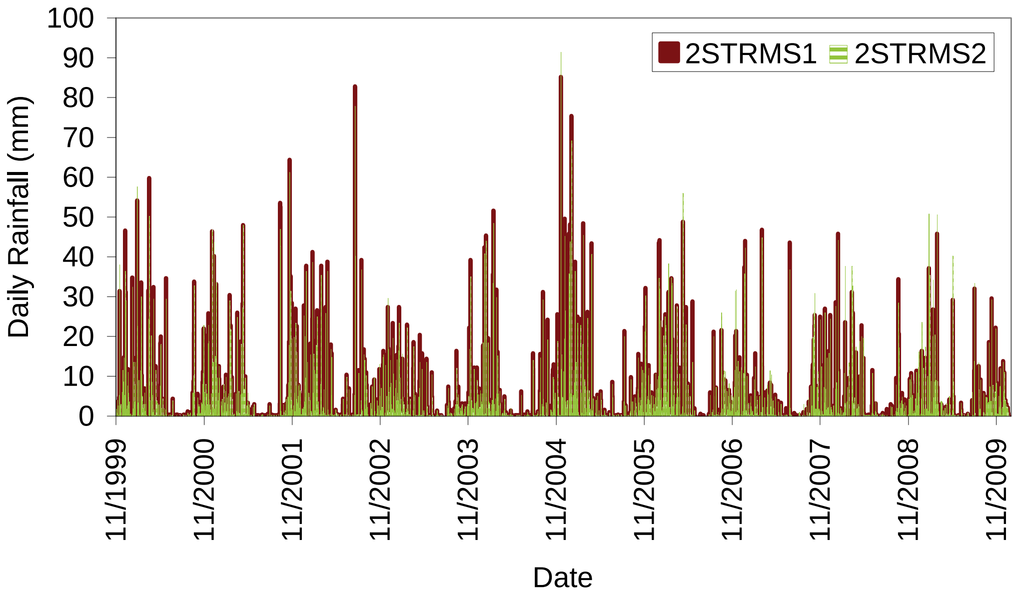


Figure 4.9. Daily rainfall totals for the two long-term rain gauges at the Two Streams study site (November 1999 to January 2009).

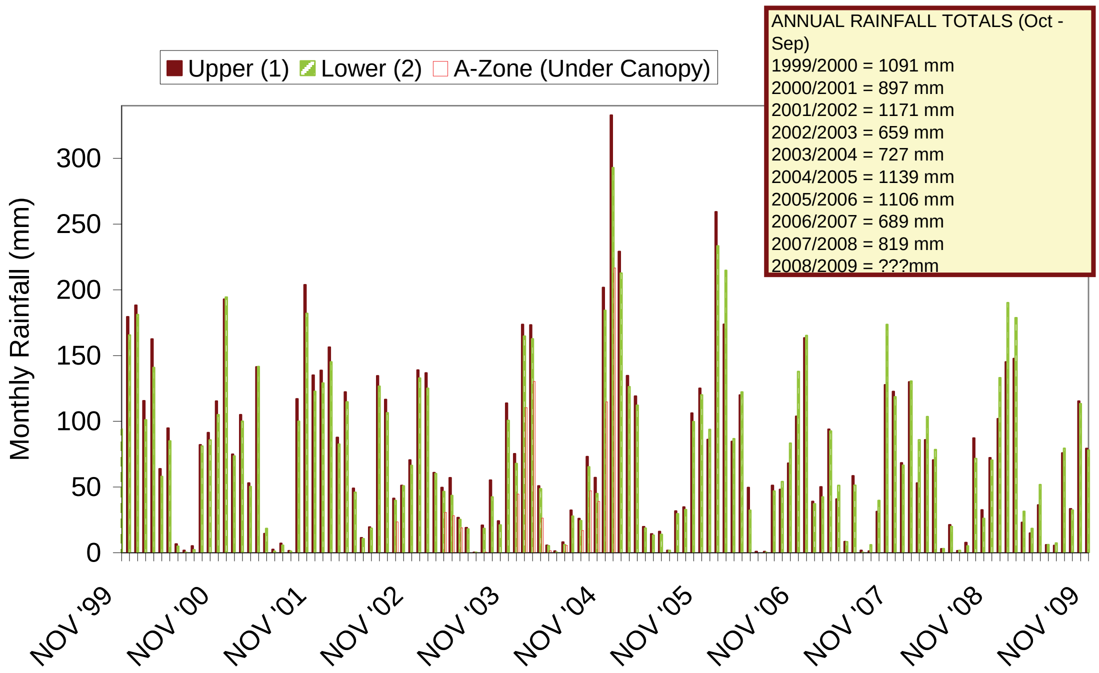


Figure 4.10. Monthly rainfall totals for the two long-term automatic raingauges at the Two Streams study site (November 1999 to January 2009) and beneath the wattle canopy at the A-Zone site (August 2002 to November 2009).

4.3 Water-use of Black Wattle

4.3.1 Large aperture scintillometer estimates of total evaporation

Long-term measurements using scintillometry over trees are very few and although De Bruin *et al.* (2002) measured fluxes using a LAS continuously for a year, no studies have been internationally published in which scintillometry has been used for 2.5 years. In addition, this work was performed over trees using masts and in a mistbelt. For this reason the integrity of the data was intensely scrutinised and checked at 10 min intervals. This is further explained in the materials and methods. For certain periods of measurement, the LAS was removed from the site for servicing and used at other research sites. In the first year it was at the site for 100 % of the time, 88 % of the time for the second year and for 30 % of the time for the first 100 days of the third year.

The Two Streams catchment is in a mistbelt and the validity of using an optical measurement system such as the LAS was of significant research interest. In the first year of the study only 8.3% of the data needed to be "patched", 5.4% in the second year and 4.5 % in the third year, demonstrating the high reliability of these data. Data loss was mainly attributed to the transition period between dawn and dusk when calculation of the sensible heat flux changes from the stable to unstable solution (see section 3.5).

Generally, on clear, windless days, F_h and L_vF_w typically follow bell-shaped curves similar but less than the R_n curve (Figure 4.11). However, in a few cases, such as 2 August 2008, F_h was unrealistically high in comparison to the net irradiance due to advection (Figure 4.12). Advection results in an addition or subtraction of energy from the system which is not accounted for in the shortened every balance equation. Advective conditions at Two Streams were typically the result of hot, dry berg winds or cold frontal winds increasing or decreasing the sensible heat flux measurements respectively. Due to the good fetch conditions, advection problems were limited to only a few extreme days.

On extreme, hot berg wind days the energy balance above the *A. mearnsii* showed unusual patterns (Figure 4.13). This pattern was characterised by the evaporation rate increasing steeply in the morning (similar to the curve for net radiation) and then decreasing sharply between 12h00 and 16h00 from 300 Wm^{-2} to less than 100 Wm^{-2}. The sensible heat flux showed a marked increase from 100 Wm^{-2} to 570 Wm^{-2} during the same period (Figure 4.13). These data suggest that the trees were under stress and were slowing the transpiration rate by closing their stomata. The sudden rise in the sensible heat flux showed that the canopy leaf temperature also increased when transpiration stopped. These data demonstrate the importance of evaporative cooling in maintaining leaf temperatures below lethal levels.

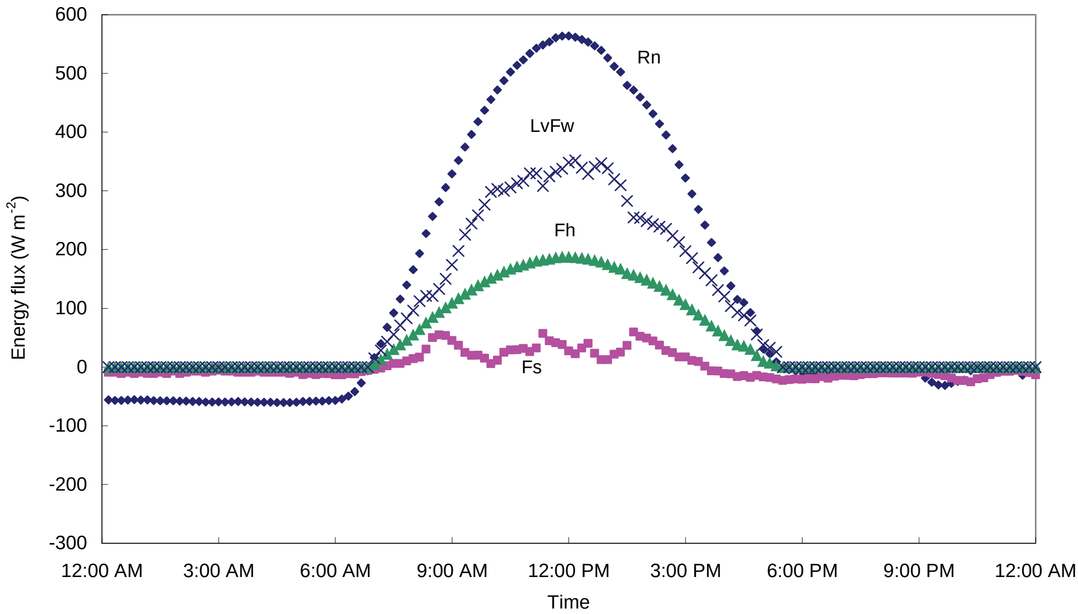


Figure 4.11. Typical values for the energy balance equation measured at Two Streams for a clear day on 8 September 2007.

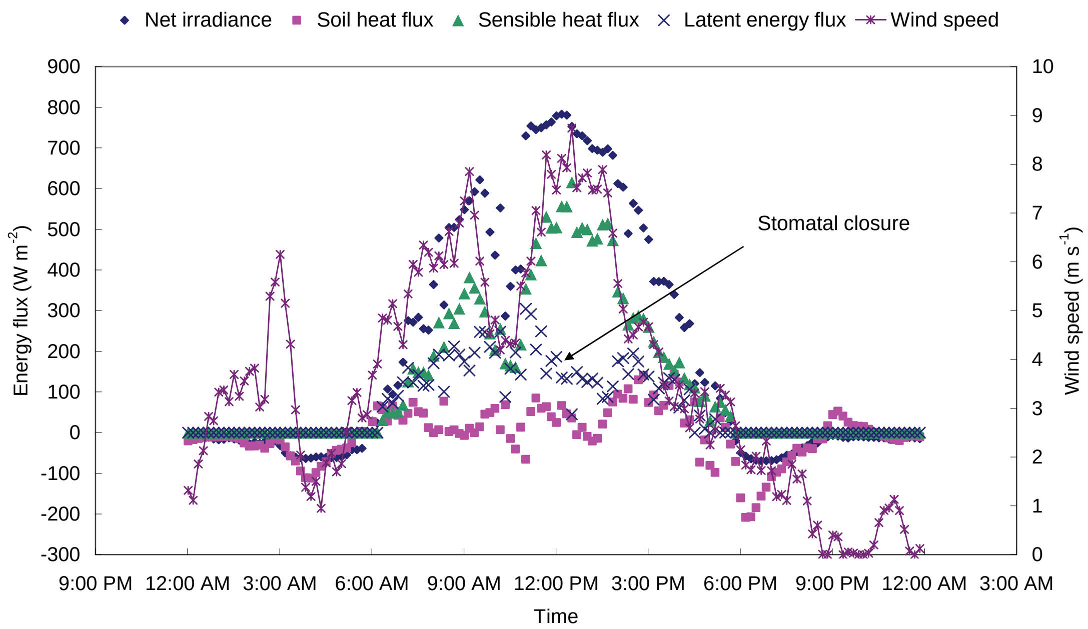


Figure 4.12. A hot berg wind on 2 August 2008 resulted in an overestimation in F_h *due to advection (*$F_h > R_n$*).*

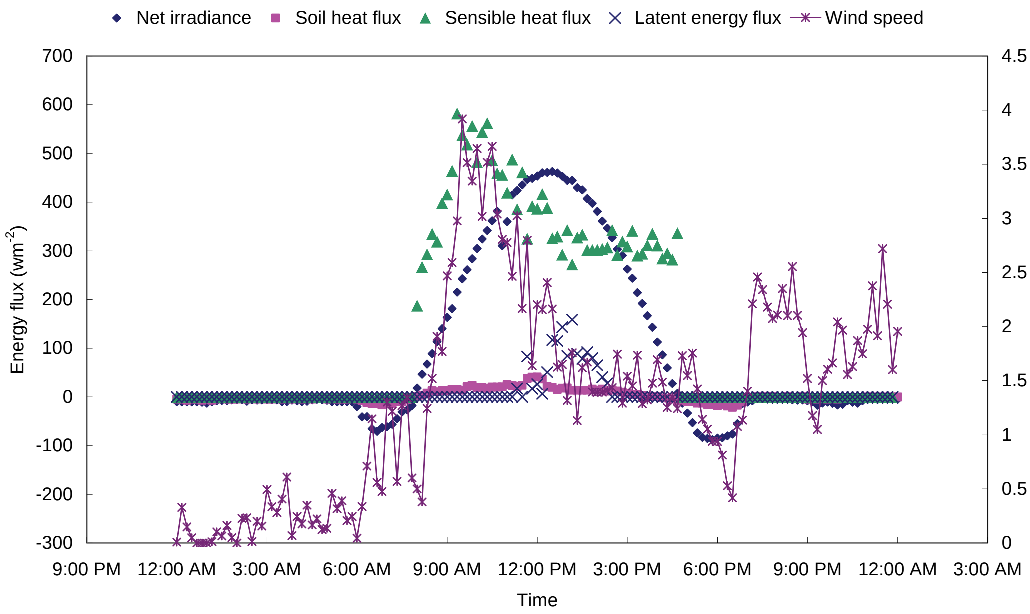


Figure 4.13. A hot berg wind on 6 November 2006 resulted in tree stress with stomatal closure as evident from a dramatic rise in F_h.

There was a strong linear relationship (R^2 = 0.94) between the available energy (R_n – F_s) and daily ET_{LAS} (Figure 4.14). Therefore, when sensible heat flux data were missing due to stable/unstable transition periods, mist or removal of the instrument from the field, the total evaporation (mm) was estimated using the linear relationship $ET = 0.351(R_n - F_s) - 0.1545$.

The daily total evaporation (ET_{LAS}) values ranged from 0 mm (on rainy days) to 6 mm on cloudless days for the first summer and 7 mm and 9 mm for the second and third summers respectively (Figure 4.15). The high frequency of cloudy days in summer resulted in a high variability in *ET* estimates. This contrasts with the winter *ET* where day to day variability was low. On clear winter days the maximum total evaporation was 2.2 mm day^{-1} in 2007 and 2.4 mm day^{-1} in 2008. This contrasts with *Themeda triandra* grassland evaporation rates measured in the Drakensberg of 7 mm in summer and < 1 mm in winter (Everson *et al.*, 1998). It is therefore the difference in the winter *ET* that is likely to have the biggest impact on the catchment water balance.

Monthly totals of *ET* from September 2006 to December 2008 showed clear seasonal trends, with the lowest values (58 mm) being recorded in June (winter) and the highest (165 mm) in December (summer) (Figure 4.16). Over the three-year period from 2006 to 2008 there was an exponential increase in the *ET* totals in the main growing period (October to December) from 305 mm, 334 mm and 417 mm for years 2006, 2007 and 2008 respectively. The 25% increase from 2006 to 2008 was ascribed to the high LAI (canopy closure) recorded in 2008 (Figure 4.4).

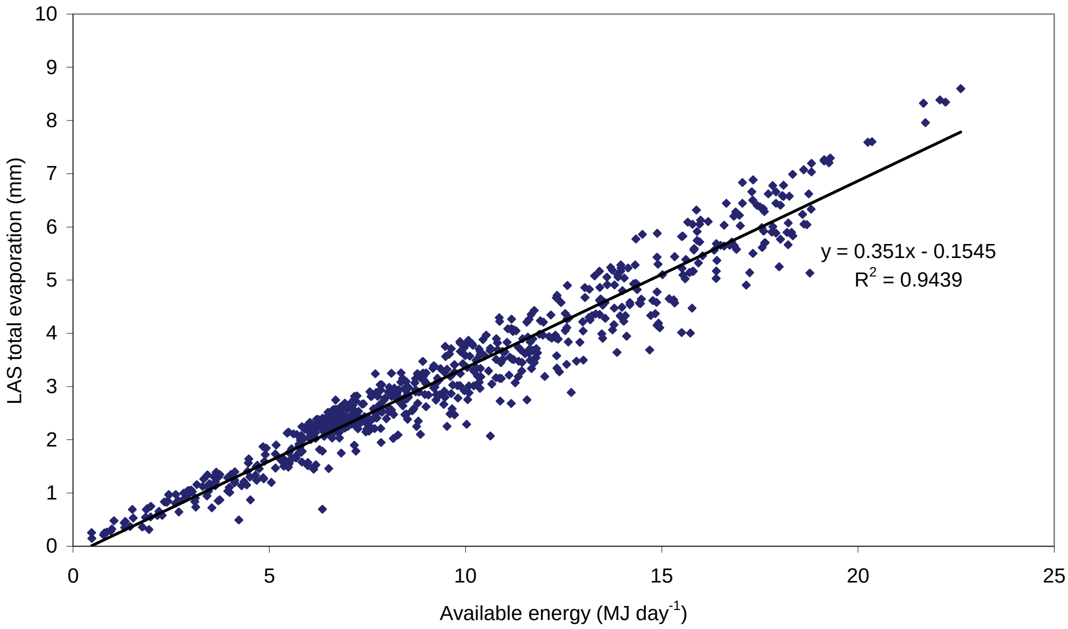


Figure 4.14. The relationship between daily ET_{LAS} *and available energy at the Two Streams site from August 2006 to December 2008.*

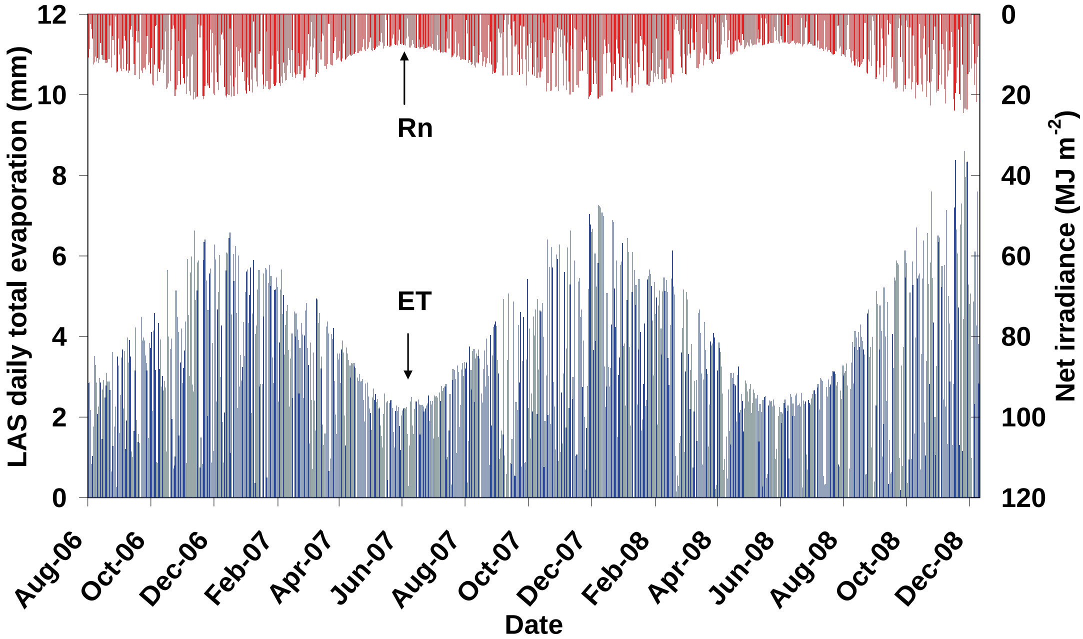


Figure 4.15. Two Streams daily total evaporation data calculated in part from a Kipp and Zonen large aperture scintillometer from 19 August 2006 to 20 June 2008.

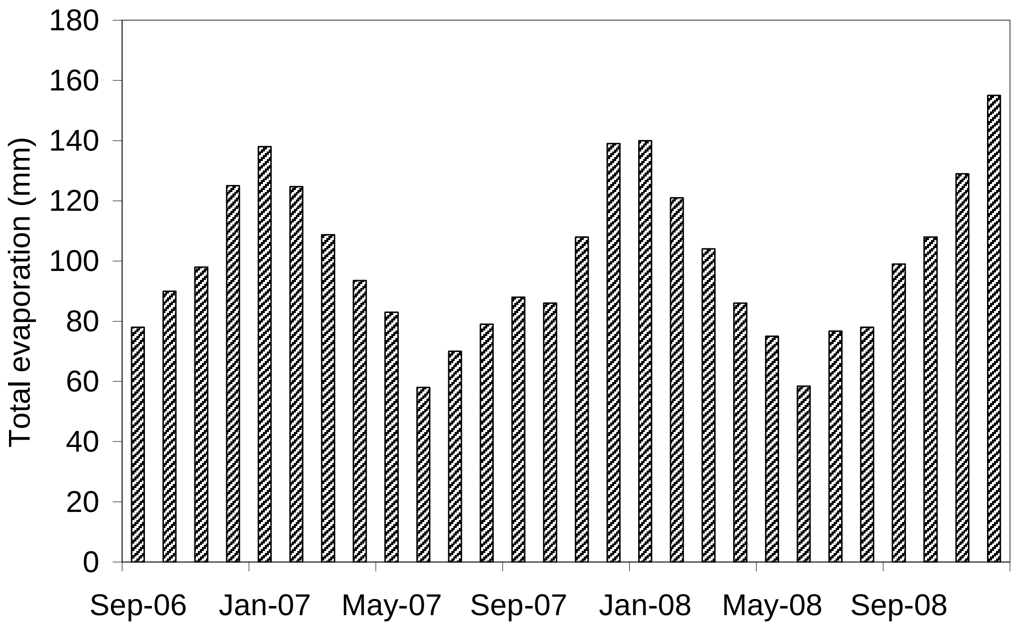


Figure 4.16. Monthly total evaporation for Acacia mearnsii *in the Two Streams catchment from September 2006 to December 2008.*

Sensible heat loss and evaporative heat loss are the most important processes in the regulation of canopy temperature and evaporation. The ratio of the two is called the Bowen ratio (β) (Campbell, 1977):

$$\beta = \frac{F_s}{L_v F_w}$$

When the evaporation rate is low, because water supply is limited, the Bowen ratio tends to be high. Thus, the Bowen ratio is about 10 for deserts, 2 to 6 for semi-arid regions, 0.4 to 0.8 for temperate forests and grasslands, 0.2 for tropical rain forests and 0.1 for tropical oceans (Nobel, 1999).

The Bowen ratio at Two Streams from August 2006 to December 2008 was generally between 0.1 and 0.4, indicating that the latent energy flux (evaporation) was the dominant process, even during the dry winter months (Figure 4.17). It is interesting to note that there was an overall decreasing trend in β as canopy closure was reached and by December 2008 the β was between 0.05 and 0.25. This is similar to the values reported by Nobel (1999) for tropical rain forests and shows the potential that the wattle trees have for high water-use.

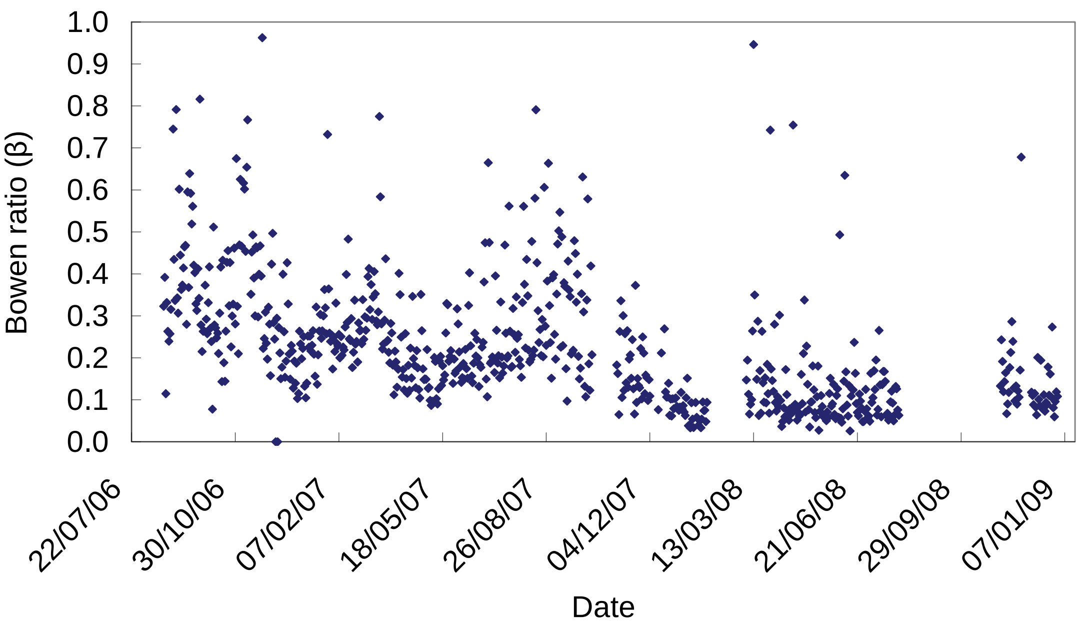


Figure 4.17. The daily Bowen ratio from 21 August 2006 to 31 December 2008.

4.3.2 Priestley-Taylor verification

Testing and verifying the different evaporation formulations is an important aspect of improving modelled *ET* in water balance models.

The LAS estimates of total evaporation were verified using the Priestley-Taylor (1972) estimate of latent energy flux:

$$L_v F_{w\ (P-T)} = \alpha \frac{\Delta}{\Delta + \gamma} \left(R_n - F_s \right)$$

where the equilibrium evaporation rate is:

$$\frac{\Delta}{\Delta + \gamma} = 0.4132 + 0.0158 T_z - 0.000115 T_z^2$$

and

$$T_z = \frac{T_{\max} + T_{\min}}{2} \qquad \text{(Savage } et\ al.\text{, 1997)}$$

where, $L_v F_{w\ (P-T)}$ is the Priestley-Taylor total daily latent energy flux (W m^{-2}) based on the equilibrium evaporation under conditions of a weak flow of humid air over a well-watered crop and α represents the advective term as a constant fraction. Priestley and Taylor (1972) found α to equal 1.26 in many studies. Δ is the rate of change of saturated vapour pressure with temperature ($kPa\ {}^oC^{-1}$), γ is the psychometric constant ($kPa\ {}^oC^{-1}$), T_{max} is the maximum daily air temperature (ºC) and T_{min} is the minimum daily air temperature (ºC).

The Priestley-Taylor method was developed for land areas neither suffering from water stress nor experiencing significant advection (Calder, 1990). Since there was a significant (R^2 = 0.94) linear relationship (y = 0.96x + 0.09) between the daily ET_{LAS} and ET_{P-T} (Figure 4.18) these results indicate that the trees at Two Streams were seldom stressed.

Comparison between the monthly totals of ET_{LAS} and ET_{P-T} were very similar (usually < 10 mm month^{-1}) (Figure 4.19). In the first year, until March 2007, the Priestley-Taylor consistently over-estimated the monthly ET. This can be ascribed to the low LAI in the first year. This situation was reversed in 2007 and 2008 following canopy closure. The Priestley-Taylor method therefore represents a simple and realistic descriptor of *A. mearnsii* water-use for trees up to three years old. This relationship may not be valid in other climatic areas where trees may experience water-stress.

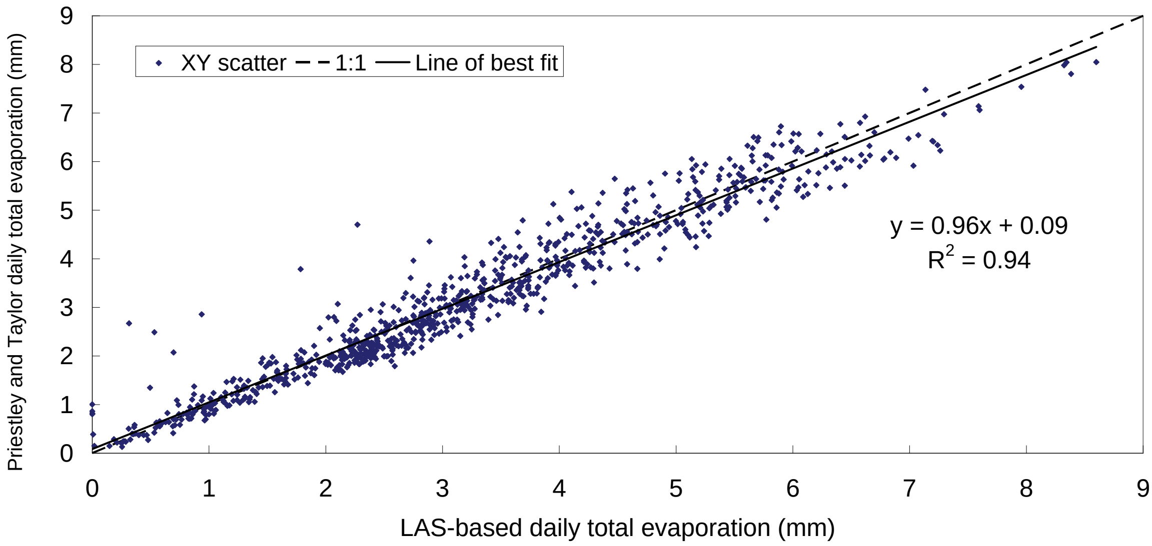


Figure 4.18. Relationship between the daily ET_{LAS} *and* ET_{P-T}.

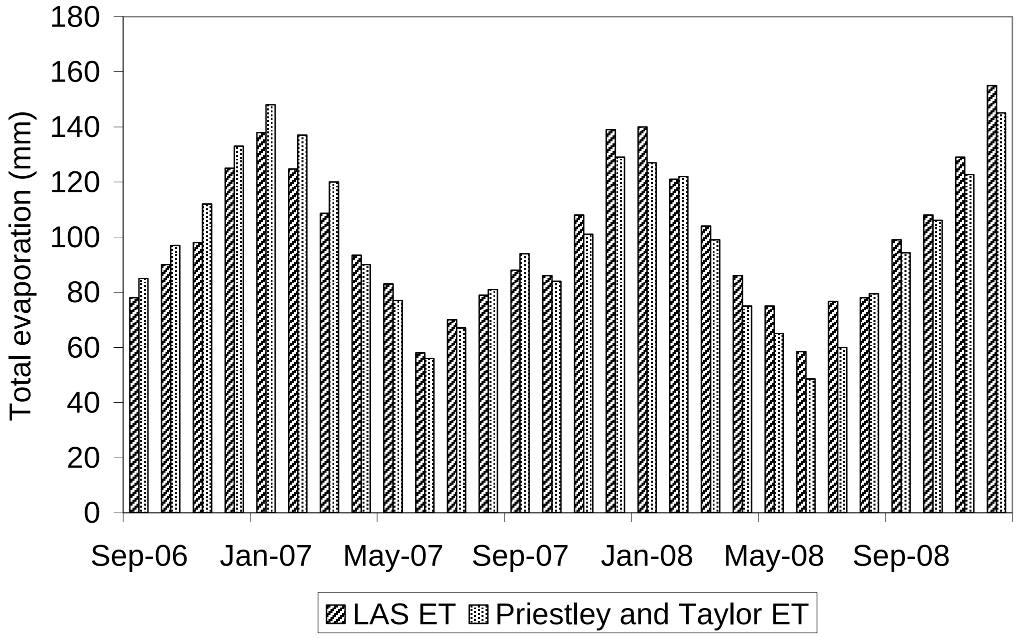


Figure 4.19. Relationship between the LAS and the Priestley-Taylor estimates of monthly total evaporation from September 2006 to December 2008.

4.3.3 Reference evaporation and crop factor for Black Wattle

The data record for the AWS used for calculating the reference evaporation begins on 14 February 2007 and ends on the 31 December 2008.

The output interval from the AWS of the standard grass reference evaporation, was hourly and daily. However, using these different output intervals resulted in differences in the estimates of the daily total reference evaporation. These differences are shown throughout the year in the time series graph of ET_{sz} where there is a consistent underestimation using the daily outputs (24 hour) as opposed to the hourly data (Figure 4.20). A comparison of these data using regression analysis showed a 13% difference between the two output intervals (Figure 4.21). Hence, where hourly data with a finer spatial resolution is available, it should be used in preference to the single daily outputs. In addition, the handbook to the ASCE-EWRI equations (Allen *et al.*, 2000) recommends that the night-time values be included in the calculation of daily ET_{sz} from hourly values. The inclusion of night-time values generally increased the daily ET_{sz} by about 2% (Figure 4.22). We followed the above procedures in all calculations of ET_{sz}.

Regression analysis between ET_{sz} and ET_{LAS} showed close agreement with a coefficient of determination of 0.85 with a slope of 1.04 (Figure 4.23). Thus using a crop factor approach will explain approximately 85% of the variation in daily tree evaporation. The daily crop factor from March 2007 to December 2008 showed large daily variations (0.5 to 1.7). However, applying a 30-day moving average reduces this variation to 0.8 in winter and 1.3 in summer (Figure 4.24). Superimposed on these results is the tree height which allows an estimation of a tree age related crop factor.

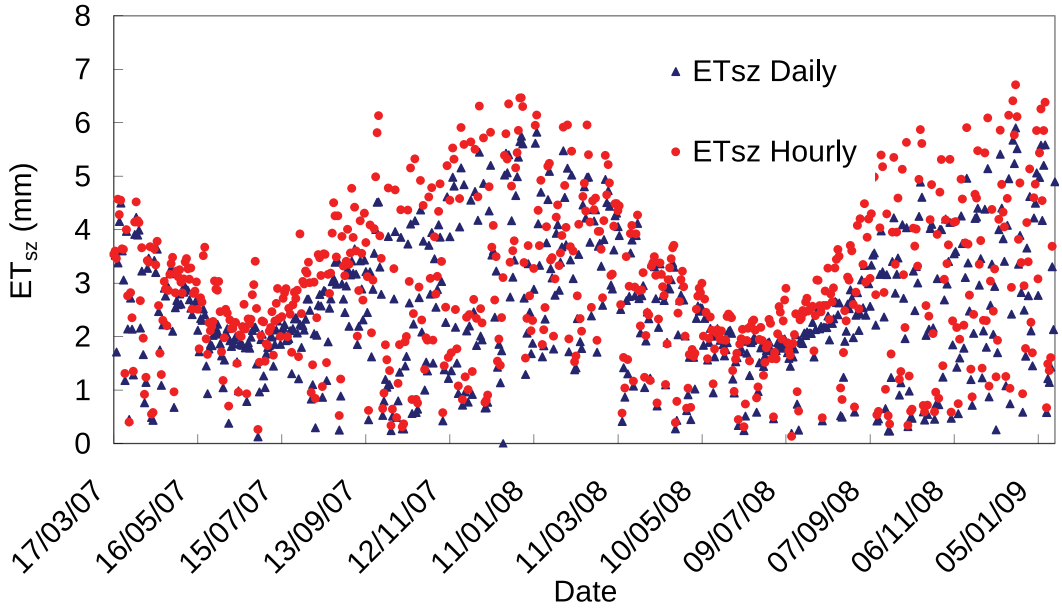


Figure 4.20. The daily values of ASCE-EWRI short grass reference evaporation (ET_{sz}*) calculated using the daily formula vs. hourly values summed to a day.*

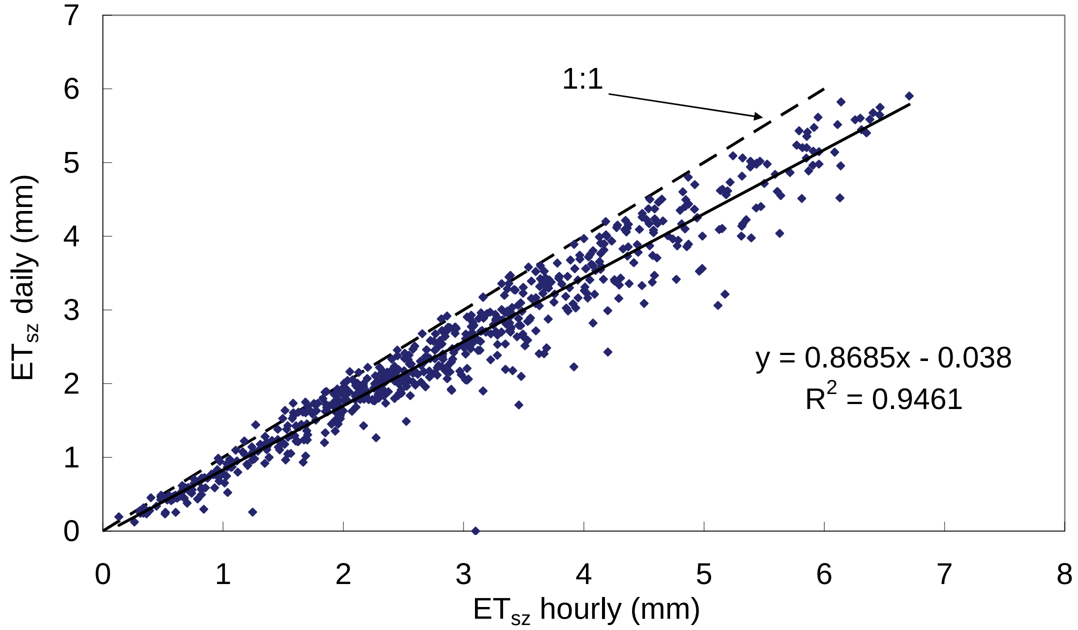


Figure 4.21. The relationship between the daily values of ASCE-EWRI short grass reference evaporation (ET_{sz}*) and hourly values of* ET_{sz} *summed to a day (including night-time values).*

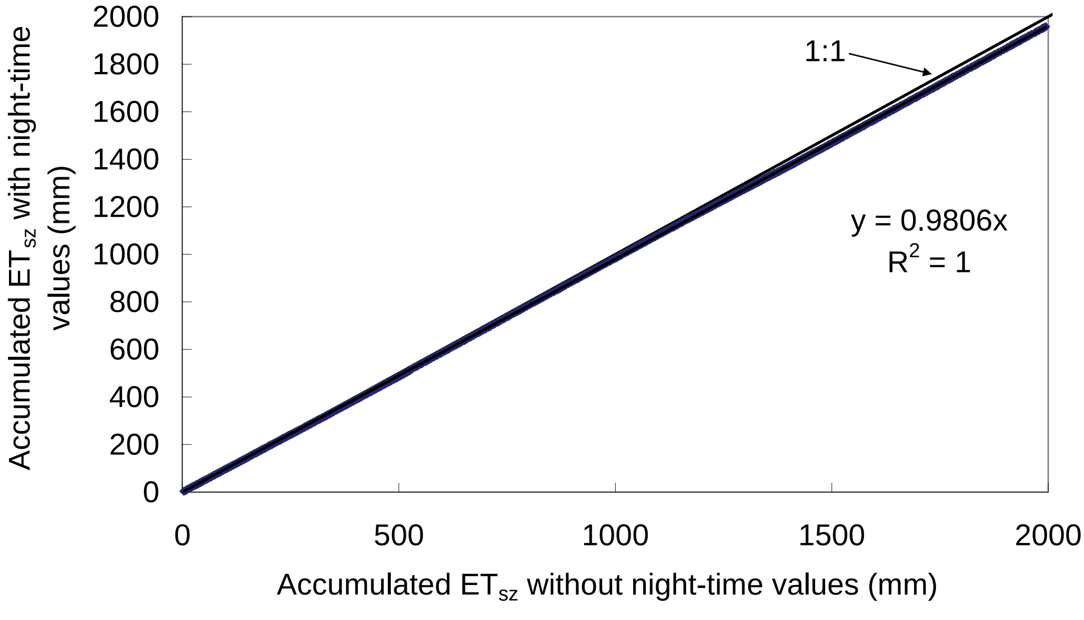


Figure 4.22. The impact of including night-time values of ASCE-EWRI short grass reference evaporation (ET_{sz}*) over a period of 21 months from March 2007 to January 2009 is 2% or 36 mm.*

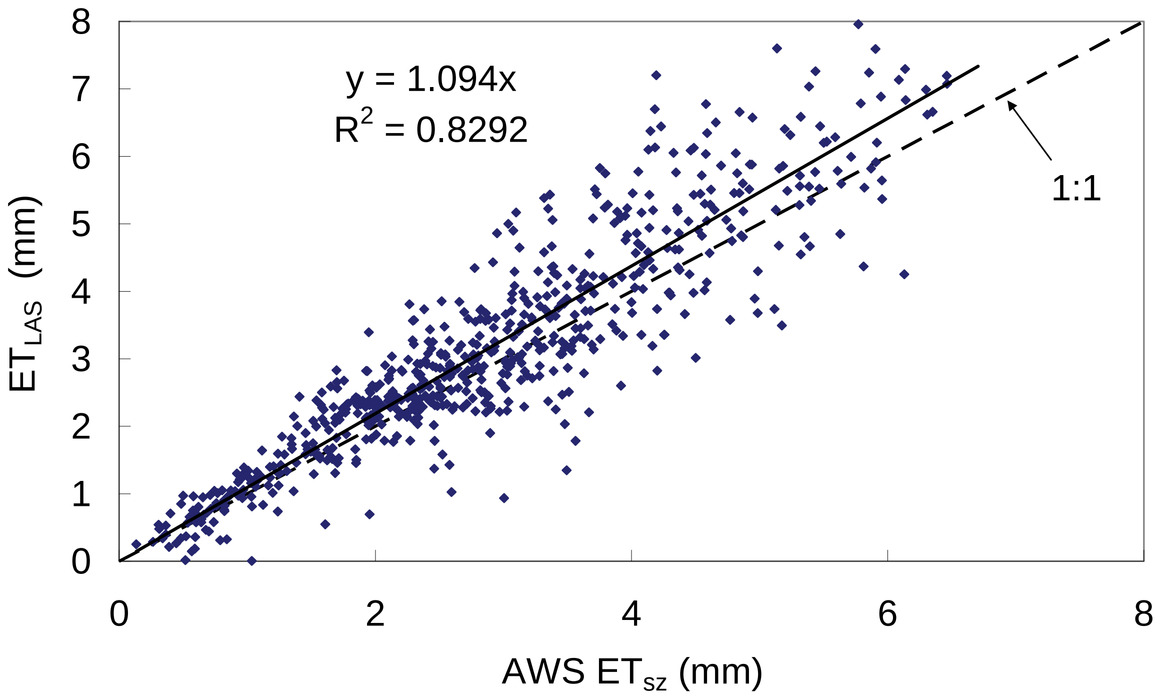


Figure 4.23. The relationship between the daily AWS short grass reference evaporation (ET_{sz}*) and the LAS total evaporation (*ET_{LAS}*) from April 2007 to December 2008.*

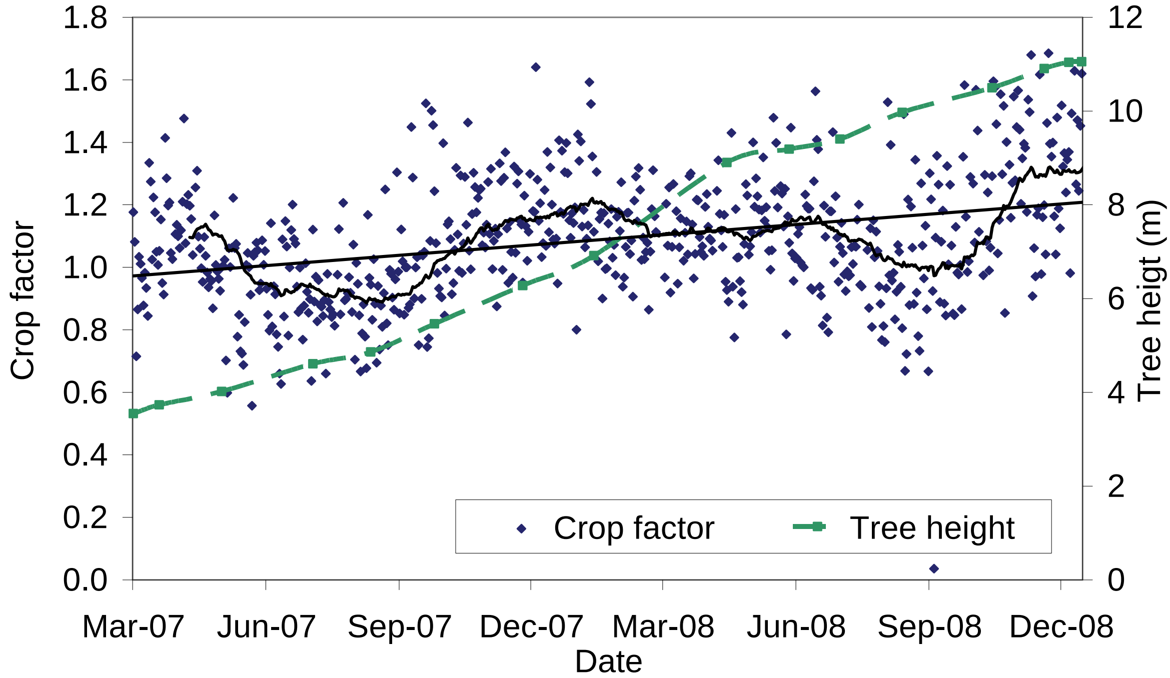


Figure 4.24. The daily crop factor calculated from ET_{sz} *and* ET_{LAS}*. A linear regression and 30-day moving average have been fitted to the data.*

4.4 Streamflow Gauging

Daily streamflow totals from January 2000 to December 2008, together with corresponding rainfall data are illustrated in Figure 4.25. These flows are calculated in terms of an equivalent depth of water over the entire catchment, enabling a comparison with rainfall. Note that the streamflow totals were plotted on a log scale in order to accentuate the lower flows. In January 2000, before clearing of the riparian areas there was no flow in the river. Riparian clearing in March 2000 resulted in continuous streamflow for nine subsequent dry seasons, including droughts in 2003 and 2007. A runoff:rainfall relationship of 0.03, 0.04, 0.01 and 0.02 for 2001 to 2004 was found for the afforested catchment with the riparian areas cleared (Figure 4.26). The complete clearing of the catchment took place in 2004 and corresponded to a significant increase in streamflow in subsequent years. New runoff:rainfall relationships were established of 0.08, 0.07, 0.08 and 0.08 from 2005 to 2008.

The replanting of the catchment at the end of 2006 does not seem to have affected the runoff:rainfall relationship of the catchment yet. It will be interesting to monitor this as the trees continue to grow.

Peak flows of 10 mm were recorded in January 2005 which coincided with the clear-felling of the catchment. Due to the exposed soil surface and impact of heavy machinery on the soil structure, significant amounts of topsoil were washed into the river and weir at this time. Based on the damage caused during these events, it is strongly recommended that tree harvesting in wet seasons in areas susceptible to erosion be evaluated with further research.

The clearing of the riparian area of trees in 2000 and clear felling of the catchment in 2004 had a significant impact on the relationship between accumulated streamflow and accumulated rainfall (Figure 4.27). An initial calibration period was established from January to April 2000 using a breakpoint analysis which has been documented in Everson *et al.* (2008) and shown to be statistically significant using an analysis of variance with a goodness of fit (R^2) of 0.995. Based on this relationship, the impact of clearing the riparian vegetation followed by clear-felling the catchment in 2004, resulted in a total gain in streamflow of 235 mm by January 2009.

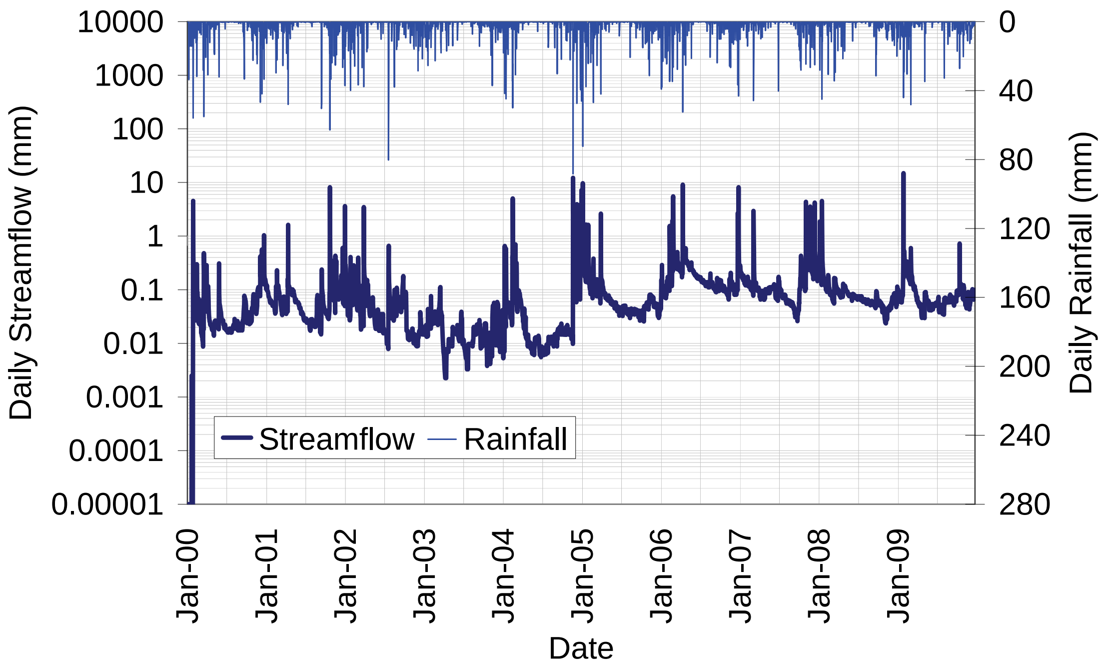


Figure 4.25. Daily streamflow totals (mm) with corresponding daily rainfall data (mm) for the treated catchment from January 2000 to January 2009.

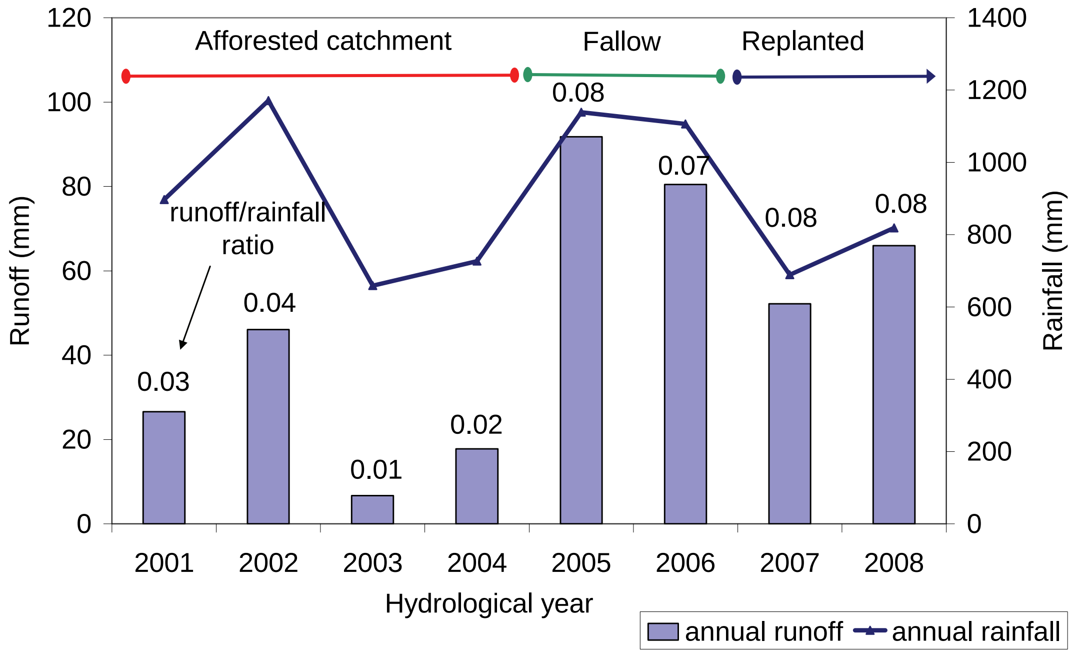


Figure 4.26. The annual rainfall and runoff measured in the Two Streams catchment also showing in text the ratio of annual runoff to annual rainfall with the different land-use in the catchment.

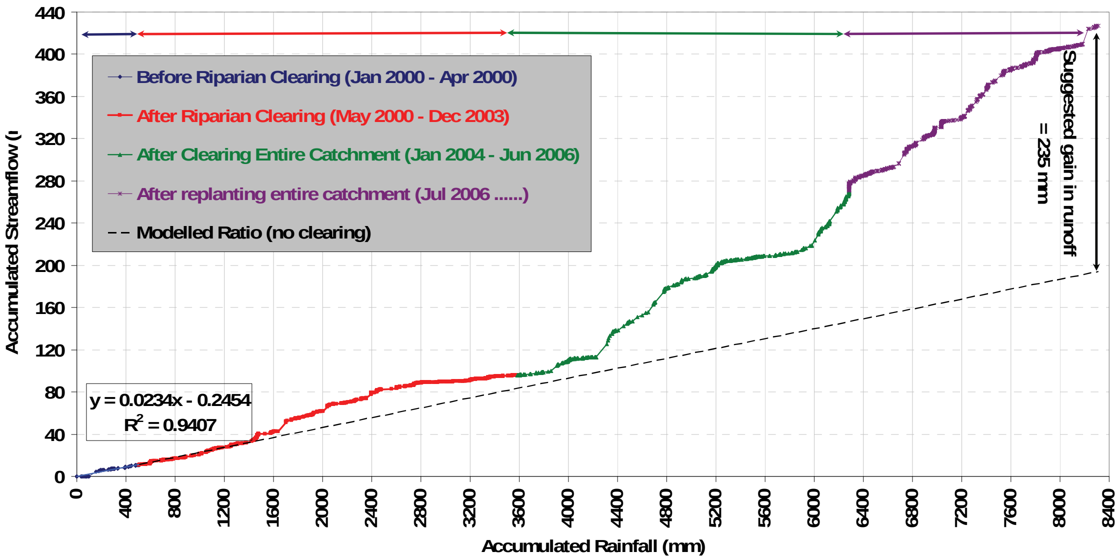


Figure 4.27. The relationship between accumulated rainfall and streamflow for the Two Streams weir for the period November 1999 to December 2008.

4.5 Electrical Resistivity Tomography Survey

The results of the resistivity survey across the wattle site are displayed in Figures 4.28 to 4.30 in the form of two-dimensional resistivity sections corresponding to Traverses 1, 2 and 3, respectively.

From the resistivity sections presented the following observations were made:

- All three resistivity sections display high resistivities at shallow depths. These high resistivities at shallow depths are typical of the resistivity surveys and may be related to the fact that the shallow earth materials are generally dry with poor conductivity. In addition, the surface of the wattle site is covered with decaying plant material that attains a thickness of approximately 0.5 m in places. The plant material is also expected to be resistive to electrical current flow, hence the observed high resistivities.
- The resistive material at shallow depths is underlain by a highly conductive layer with resistivity values that range between 60 and 180 Ohm m^{-1}. This low resistivity layer is in all likelihood due to the presence of weathered earth material. Shallow boreholes (5 m deep) drilled on the wattle site prior to the resistivity survey revealed the presence of a thick clay/silt layer. Clays are often highly conductive and the low resistivity layer may be associated with these materials.
- Although the presence and depth of a perched water table cannot be identified from the resistivity sections, the observed low resistivity values suggest that the weathered layer is at least partially saturated.
- The conductive layer is underlain by material of a high resistivity that is thought to be the unweathered bedrock. Comparison of the resistivity sections of Traverse 1, 2 and 3 indicates that the depth to the bedrock increases as one moves up gradient (in a north-westerly direction) from Traverse 1 to 3. The thickness of the highly resistive materials at shallow depth also seems to increase.

The interpreted boundaries between the highly resistive surface material, the conductive layer representing the weathered material and the bedrock layer along Traverses 1, 2 and 3 are shown in Figures 4.28 to 4.30 in terms of depth below ground surface.

In order to obtain better estimates of the true depths of the boundaries, geological borehole logs were kept from the drilling operations to allow calibration of the inverted resistivity data (Appendix B). This confirms the presence of deep clays with high water contents to depths of 25 m. This represents a significant soil water storage reserve for access by deep rooted trees.

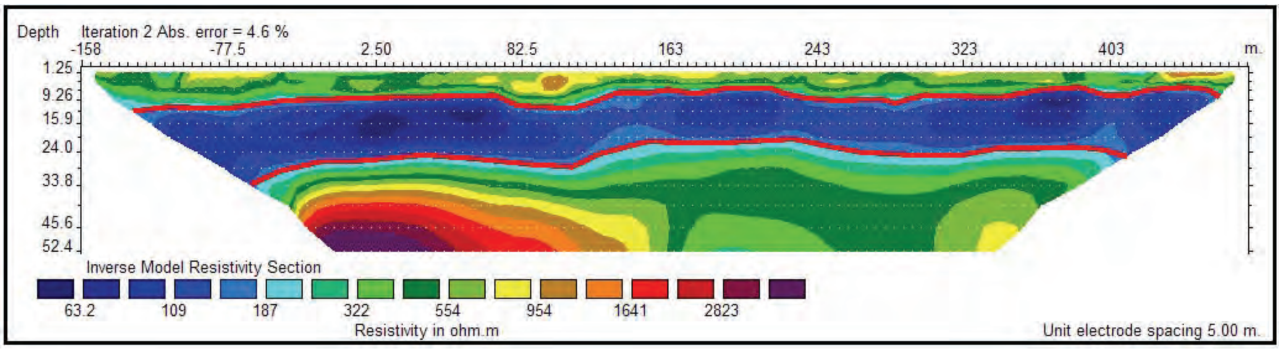


Figure 4.28. Interpreted boundary depths along Traverse 1.

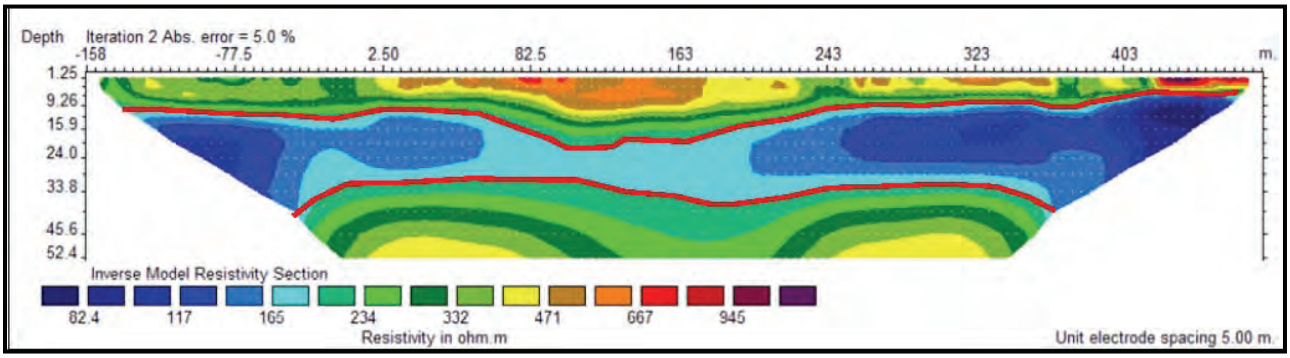


Figure 4.29. Interpreted boundary depths along Traverse 2.

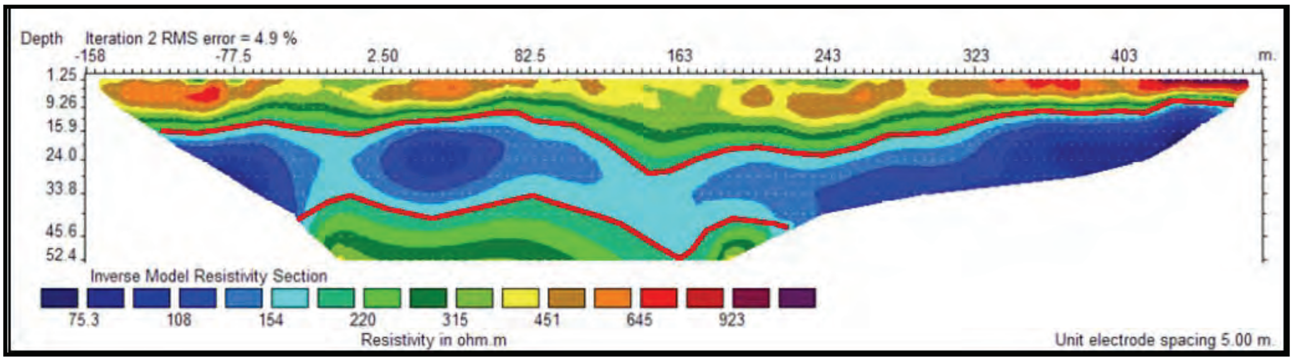


Figure 4.30. Interpreted boundary depths along Traverse 3.

4.6 Groundwater

The water levels were measured manually at monthly intervals (Figure 4.31). The deep borehole (south) had the longest record of data. It fluctuated by approximately 5 m, dropping in winter and rising in summer. The newer boreholes (centre, northern, western) behaved in a similar way. Although the record is still short, they appear to peak in December followed by a gradual recession into winter reaching a maximum depth in October. This was followed by a period of relatively steep recharge over a two month period back to the summer levels.

The northern borehole had the highest elevation above mean sea level and had a water depth approximately 10 m deeper than the other boreholes. There was a noticeable difference in the recharge with distance from the stream. Those boreholes closer to the stream responded first to the wet season. The delay between the start of the recharge in the centre borehole and the western borehole (most delayed) was approximately one month in 2008.

Based on the south borehole with the longest record, the dry season water level dropped from 35 m in 2007 to 36 m in 2008 despite a rainfall of 689 mm in 2007 and a higher rainfall of 819 mm in 2008. This may be as a result of the impact of the trees on the recharge rate.

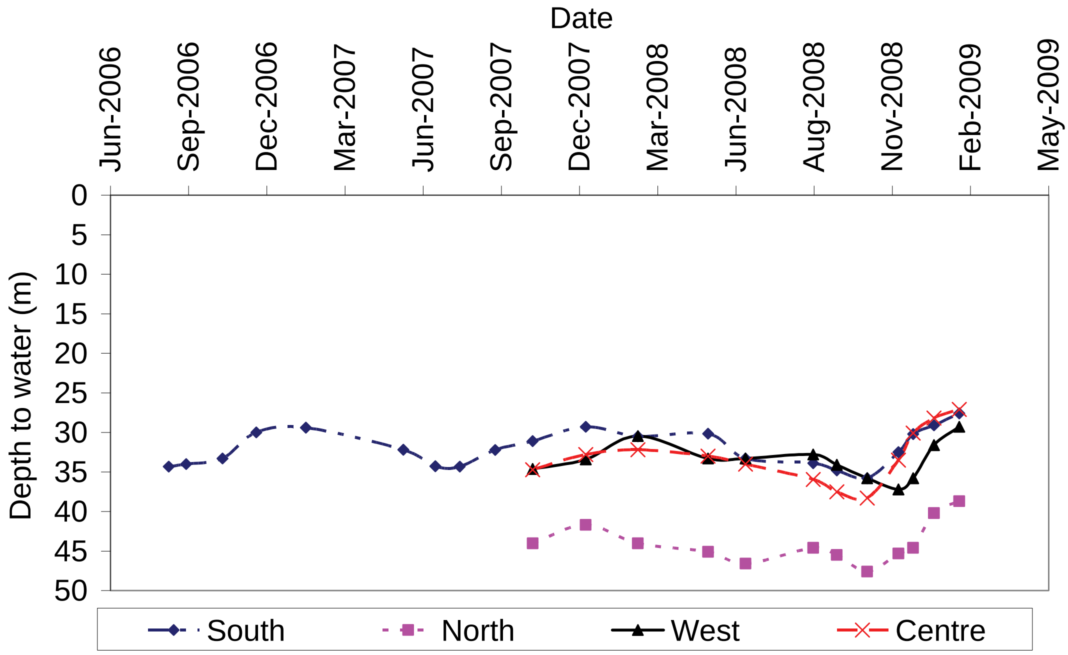


Figure 4.31. Water levels in boreholes in and around the LAS site.

4.7 Soil Water

CS616 sensors at the site produced error-free data (despite being difficult to install) to a depth of 2.4 m. Surface probes at 0.4, 0.8 m and 1.2 m depths showed a high variability in fractional volumetric soil water content in response to dry and wet periods (12 to 27%). Beyond 1.6 m the results were higher but less variable (30 to 35%) (Figure 4.32). In general, volumetric soil water content increased with increasing depth.

Daily trends in the CS616 volumetric water content at a depth of 2.4 m showed a steady decline in water content from 40 to 32.4% in the 2007 dry winter period (March to September). The response of the water content at 2.4 m to the spring rains was noticeably delayed until mid-October 2007. By this time 175 mm of accumulated rainfall had already fallen. By the end of December 2007 the volumetric water content had only increased to 34%, despite a further 223 mm of rainfall (398 mm from 1 September to 31 December). In 2008 there was a gradual drying out of the profile at 2.4 m, reaching a minimum of 30.4% in December 2008. There was no noticeable response to the 302 mm of summer rain (1 September to 31 December). This was likely the result of the combined response of the soil water to the high level of water-use shown by the trees (Figure 4.15) and the unusually low early summer rains recorded in 2008. The soil water contents at 2.0 m and 1.6 m closely followed the trends of the 2.4 m depth, although they were generally more responsive to the summer rainfall events (Figure 4.32).

The cylindrical TDR probes installed to a depth of 4.8 m at 0.4 m intervals provided reasonably good data although there was significant noise in the data during the summer months. For this reason only two of the depths (1.6 and 4.8 m) have been shown together with the 0.40 m surface measurement using a commercially available CS605 probe (Figure 4.33). In future, the probe lengths will be increased in order to improve their consistency and reduce this noise. The soil was drier than the rest of the profile at 1.6 m and significantly wetter at 4.8 m (Figure 4.33). Volumetric water content in the deep profile was high (45%) and close to saturation. This value is high, even for soils with high clay contents. At 4.8 m there was no recharge of the soil water during the summer of 2007/2008 and there was subsequently a steady reduction in the volumetric water content to December 2008. For example, in December 2007 the volumetric water content was 42% whereas in December 2008 it was approximately 32%. This represented a significant drying out of the soil profile which coincided with very high water-use of the trees and low rainfall in the 2008 summer season. These trends were similar to the CS616 probes values presented earlier.

Soil water potential measurements were made with watermark sensors installed to a depth of 4.8 m (Figure 4.34). The sensors were installed during summer and showed a gradual drying out of the profile at all depths between January and September 2008. The spring rains in October 2008 resulted in an immediate response in the surface water potential which rose from -300 to < -100 centibars. The driest layer was found at 1.6 m where the water potential dropped steadily from -145 to -360 centibars over the 12-month period (Figure 4.34). This shows good agreement with the cylindrical TDR probes where the 1.6 m depth was also dry. All the deeper probes (2.4 m to 4.8 m) followed similar trends but were not as dry as at 1.6 m. The 4.4 m and 4.8 m depths were consistently “wet” in the range of -100 to -200 centibars for the entire period. The measurements of soil water potential therefore also support the evidence from the water content measurements of a consistent drying out of the soil profile to depths of 4.8 m.

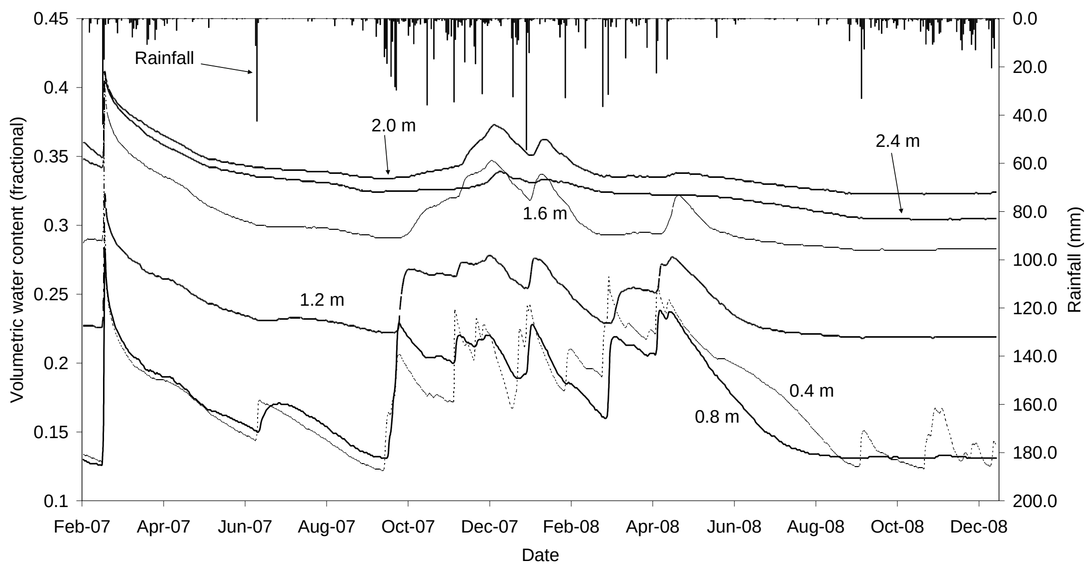


Figure 4.32. Volumetric soil moisture measured with CS616 probes to depths of 2.4 m from February 2007 to December 2008 at Two Streams.

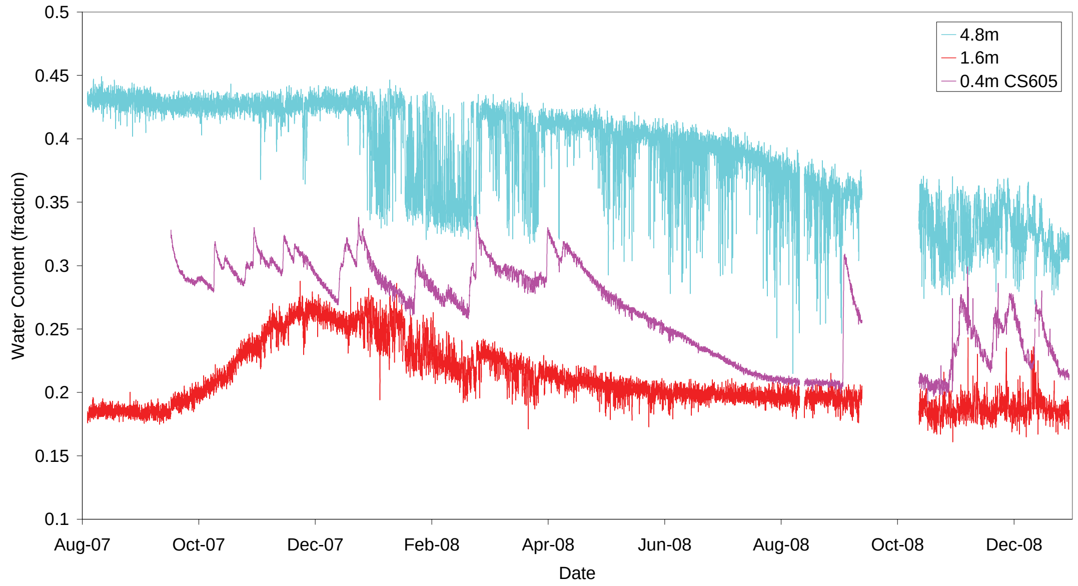


Figure 4.33. The volumetric soil water measured with cylindrical TDR probes to a depth of 4.8 m from August 2007 to December 2008.

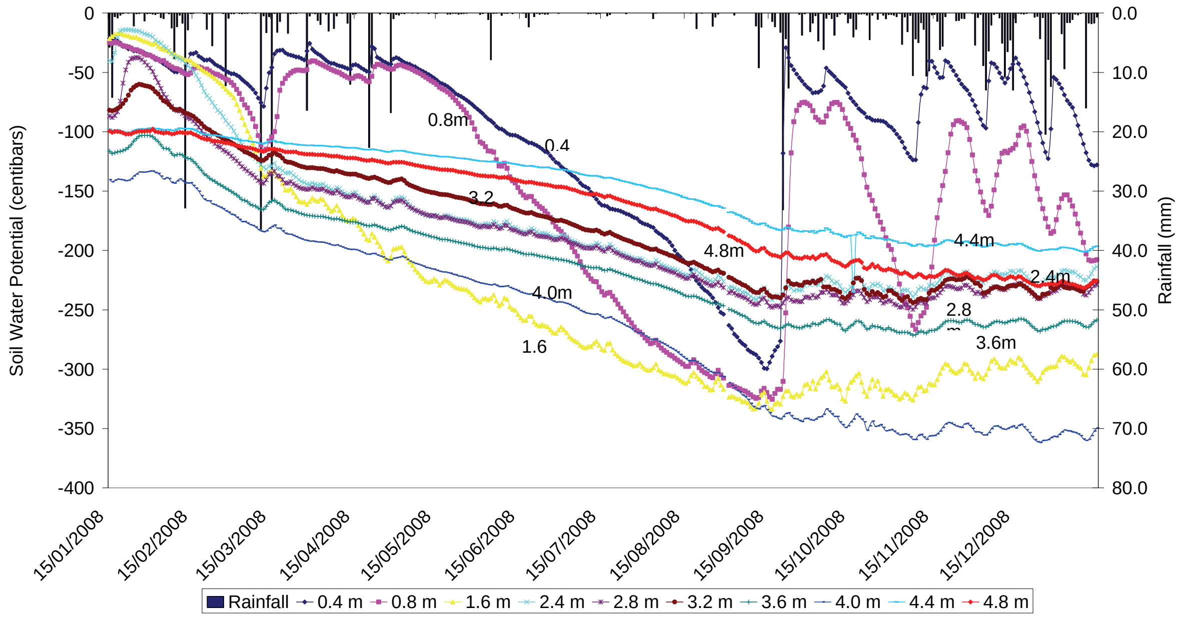


Figure 4.34. Results of soil water potential measured with watermark sensors to a depth of 4.8 m.

4.8 Monthly Water Balance

Burger (1999) used Bowen ratio technology to measure the evaporation in the Two Streams catchment over commercial forestry areas and found that the evaporation exceeded the rainfall by 45%. Between August 2006 and December 2008 the accumulated values of rainfall and total evaporation using the LAS were 1921 mm and 2851 mm respectively (Figure 4.35). Evaporation from the developing wattle plantation therefore exceeded the rainfall by 46%, confirming the previous Bowen ratio measurements. Over the same period, estimates of evaporation using the Priestley Taylor formulation were 2781 mm and therefore very similar to the LAS *ET* (a difference of only 2.5% or 70 mm). The accuracy of the Priestley-Taylor equation has been validated by a review of 30 water balance studies in which it was commonly found that, in vegetated areas with no water deficit or very small deficits, approximately 95% of the annual evaporative demand was supplied by radiation (Stagnitti *et al.*, 1989). Morton (1983) notes that the value of 1.26, estimated by Priestley-Taylor, was developed using data from both moist vegetated and water surfaces. Morton recommended that the value be increased slightly to 1.32 for estimates from vegetated areas as a result of the increase in surface roughness (Morton, 1983; Brutsaert and Stricker, 1979). The results of this study confirmed these observations, since it was found that the available energy described 93% of the *ET* (Figure 4.14) and that the Priestly-Taylor *ET* estimates were about 5% lower than *ET* (Figure 4.35). The implication of these results is that the wattle trees were using water at rates higher than the equilibrium rate throughout the year and that there was always some component of advective energy that increased the actual evapotranspiration. This means that true equilibrium potential evapotranspiration rarely occurred at the study site. Clearly water was not a limiting factor to the wattle growth during its first three years of development.

A deviation from the 1:1 line of accumulated rainfall and ET_{LAS} began on 13 January 2007 (accumulated rainfall = 400 mm) when the ET_{LAS} increased significantly relative to the accumulated rainfall (Figure 4.35). At this time the trees were well established with an average height of 2.6 m and an LAI of 1.21. This was an unusually dry summer spell, only 90 mm of rainfall being recorded between January and February 2007, compared with 440 mm in 2006 (Figure 4.9). Step changes were also evident in the winters of 2007 and 2008. These significant changes in slope of the rainfall – ET_{LAS} curve were a direct result of the continued high transpiration rates from the trees combined with the low rainfall at these times. This suggests that the trees were using the soil water reserves.

In the 2007/2008 growing season the slope of the rainfall – ET_{LAS} curve was the same as the 1:1 line showing that the rainfall was equivalent to the ET_{LAS} during summer. A similar trend appears to be developing in the 2008/2009 growing season.

The deviation of the evaporation excess over rainfall for the 28 month period was 46 %. In November 2007 and November 2008 the data showed that the total evaporation exceeded rainfall by 65 % and 33 % respectively indicating the importance of long-term measurements to account for unusual seasonal fluctuations in rainfall.

In the catchment water balance for Two Streams, rainfall was considered a positive gain into the catchment, while total evaporation (*ET)* and streamflow (*Q*) were considered losses. Changes in soil water storage (ΔS) were either losses or gains. Monthly totals of these four measured parameters from April 2007 to December 2008 showed that evaporation was the most dominant variable, with monthly losses ranging from -58 mm in June to -155 mm in December (Figure 4.36). Although the rainfall inputs peaked at 172 mm in summer, there was little rain in the winter period when monthly values approached zero. By contrast, the monthly streamflow was an order of magnitude smaller than the *P* and *ET* and generally less than 4 mm. In the winter months, when rainfall was very low and evaporation continued at potential rates, there was a deficit in the monthly soil water balance of about -50 mm (Figure 4.36). Not surprisingly recharge in the upper 2.4 m of the soil profile generally coincided with months of high rainfall. For the 17 month period from April 2007 to December 2008 there was a total input of +1308 mm of rainfall. Combined losses of *ET* and *Q* were -2120 mm and the measured change in soil water storage in the upper 2.4 m soil profile was -141 mm. Unaccounted for losses were therefore -671 mm over 17 months or approximately -40 mm per month. These deficits in the water balance could only be supplied from the deep soil water stores beyond 2.4 m. These data are evidence that the wattle trees, whose roots went deeper than 4.8 m (Figure 4.8), were able to access the deep groundwater reserves.

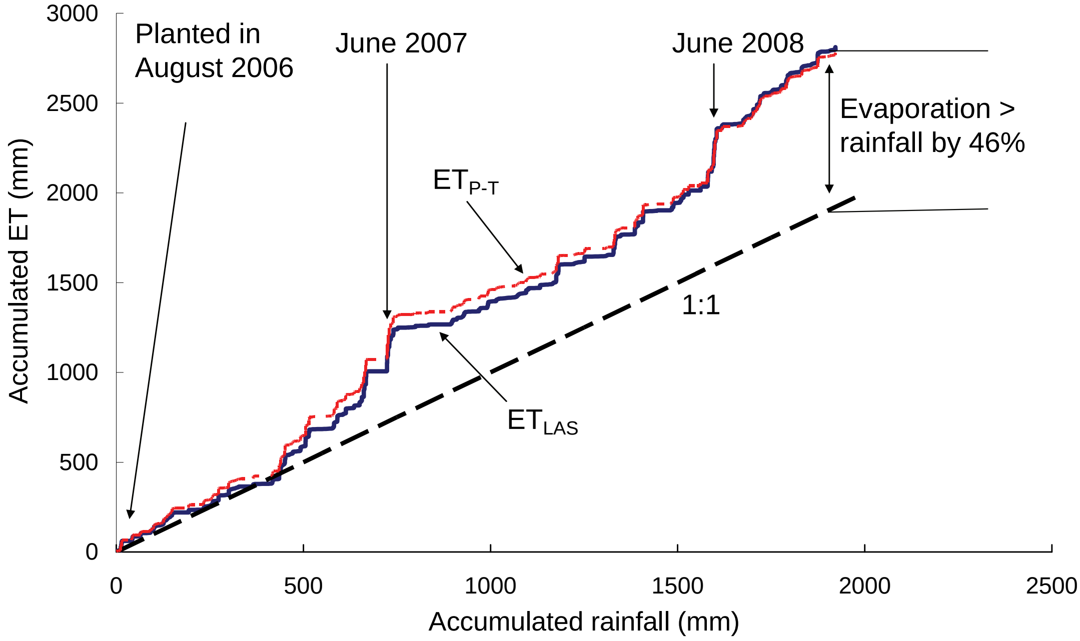


Figure 4.35. A comparison between ET_{LAS}, $ET_{P\text{-}T}$ *and rainfall from August 2006 to December 2008.*

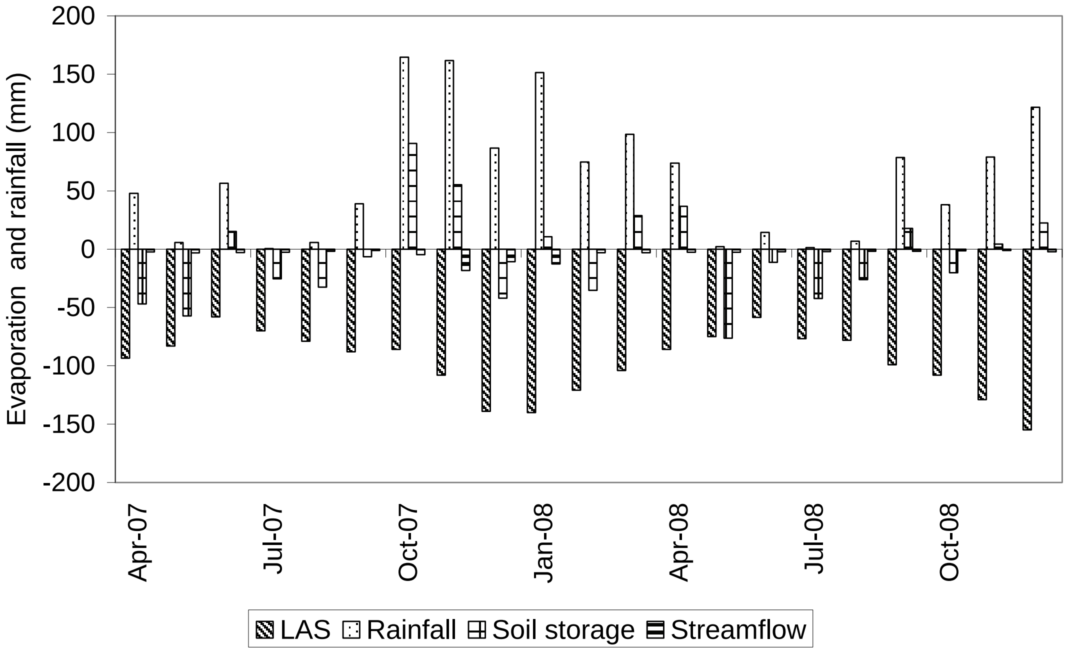


Figure 4.36. Monthly water balance showing rainfall and a positive change in soil water storage as additions (positive) and total evaporation, streamflow and soil water deficits as subtractions (negative) from the system.

4.9 Hydrological Modelling

4.9.1 Soil water modelling

Both the WAVES and ACRU simulated soil water results are shown together from January 2006 to December 2008 (Figure 4.37). The actual values of soil profile water content have been included from September 2007 to December 2008 providing a validation period of 16 months and a warm-up period for the models of 20 months. For ease of comparison, the soil water contents (both modelled and actual) are presented as the total profile water content which integrates the top 2.4 m of the soil profile by converting the volumetric water content into a depth equivalent of water in mm. The CS616 probes were used for the actual measurements, since they provided the longest deep soil profile data set at the site, down to 2.4 m. The actual total profile water content ranged from a minimum of 517 mm at the end of the long winter period

(October 2008) to 681 mm of water in mid-summer (December 2007), after approximately 300 mm of summer rainfall since the beginning of October 2007 (Figure 4.37).

A comparison of the actual and the modelled total profile water contents over the 16 month period showed that at the start of the verification period, WAVES (561 mm) was very similar to the actual total profile water content (547 mm) whereas ACRU was fairly different at approximately 400 mm (Figure 4.37). During the remainder of the simulation period it was noticeable that the ACRU model values remained fairly constant throughout the year, with only small responses to the large rainfall events discussed previously. By contrast the WAVES model showed good agreement to the trends in the actual total profile water content. Generally the WAVES model tended to overestimate the response to summer rainfall events. Particularly good agreement was found between the actual and Waves model values in the recession of the water content curves following large rainfall events.

With the advent of the summer rains in October 2007, there was a step change in the water content in the WAVES predictions, causing the model to consistently over predict the water content for the rest of summer (Figure 4.37). However the WAVES model still mimicked the actual water content values for the remainder of the season including the recession into winter 2008. By contrast the ACRU model initially responded well to the first summer rains in October 2007, but then showed a gradual decrease in values when the actual values and the WAVES model were increasing in late December 2007.

In WAVES, the exaggerated increase in profile soil water content seen at the onset of rain could be attributed to a number of factors. Excess infiltration in the simulations could be taking place which may be an indication that the soil texture classes should be modified. In Figure 3.38, the actual volumetric soil water content at 0.4 m is shown together with two modelled estimates of volumetric soil water content at 0.4 m. In these two runs, the surface layer was changed from clay loam to loam. The impact is significantly reduced volumetric soil water contents of about 8% on average. This would of course impact on the soil profile water content and could be used to improve the results of the WAVES model in Figure 4.38. The aim of the modelling was, however, to input measured values, such as soil texture, and validate the results rather than adjust model inputs to achieve measured results.

In the WAVES setup, there are a number of vegetation parameters available to accurately describe the characteristics of the crop which can have a significant impact on the soil profile water content. The most significant of these was found to be leaf/stem ratio, maximum assimilation rate, respiration and leaf mortality. Unfortunately, although this provides the user with the ability to closely define the crop, many of the parameters then require estimation as they are not known for all species. For establishing the correct vegetation parameters total evaporation was also used to assess the model performance as these values were available at the site where there is a large aperture scintillometer used to estimate sensible heat fluxes. Leaf area index and tree height were also output from the model and were used to check crop growth.

Differences in modelled and actual soil water values are illustrated by plotting the percentage deviation of the modelled values from the actual soil water values (i.e. Actual minus Modelled) (Figure 4.39). These data revealed that the WAVES values were within 20% of the actual values for 95% of the time while the ACRU model values were within the 20% range for only 5% of the time. Further work will be conducted on the ACRU runs in order to improve the simulations. The data presented here have demonstrated the value of actual long-term soil water data from deep profiles for improving model development.

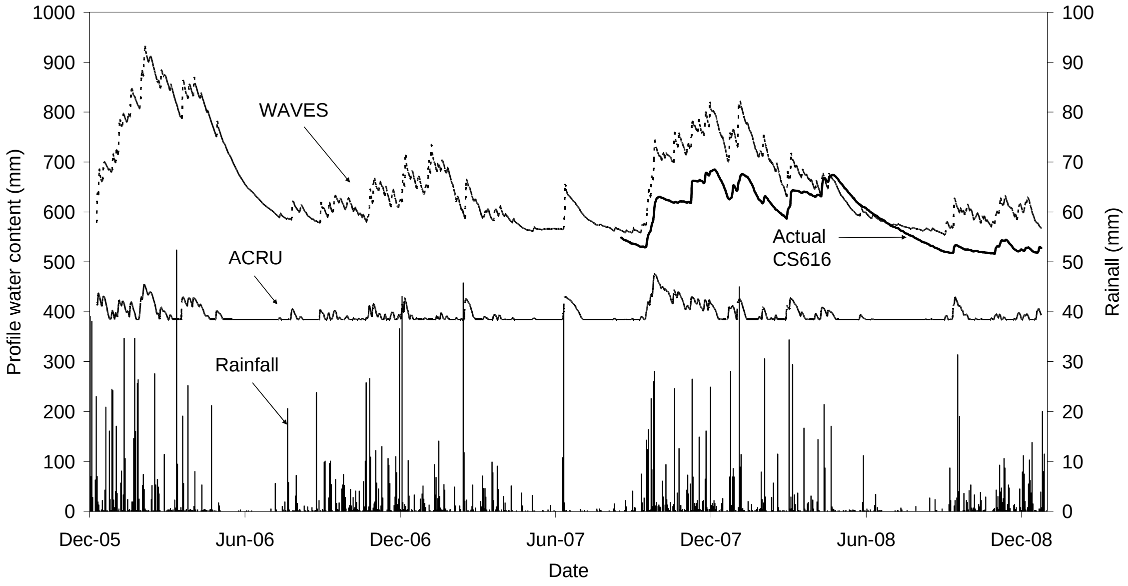


Figure 4.37. A comparison between the soil profile water results obtained from the models (WAVES and ACRU) and the actual measured results together with the daily rainfall.

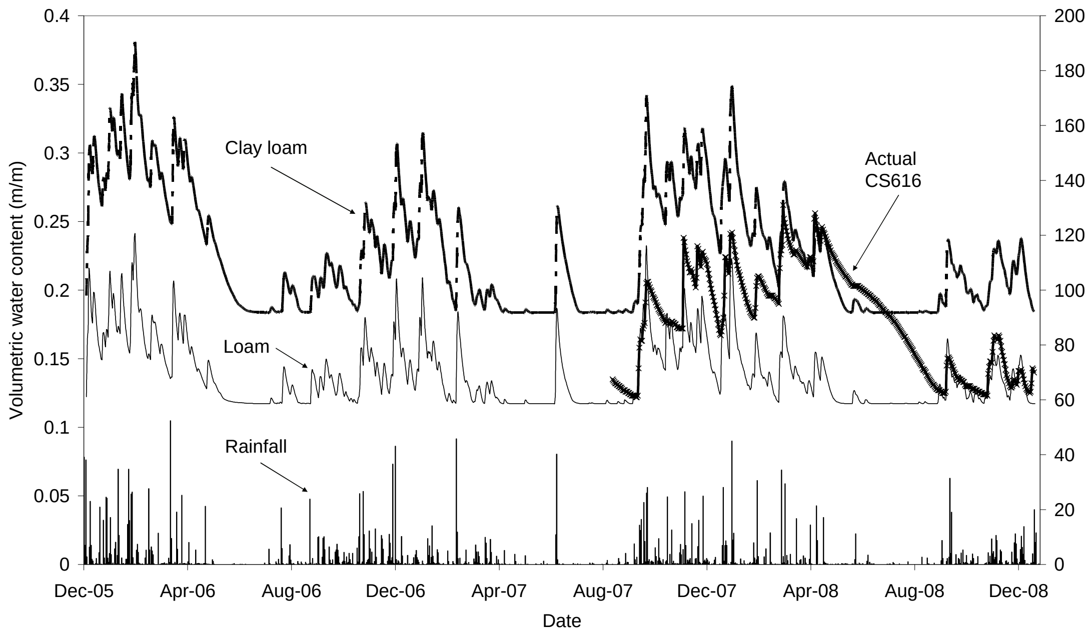


Figure 4.38. The actual volumetric water content of the profile at 0.4 m with two WAVES simulations of the volumetric water content for a clay loam and a loam.

4.10 Streamflow modelling

The streamflow simulations using ACRU show that the accumulated streamflow over time is underestimated (Figure 4.40). During the period of measurement from January 2000 to December 2008, the measured accumulated streamflow is 400 mm. The simulated total streamflow using the "old" and the new ACRU versions were 300 mm and 275 mm respectively. The simulation tracks the actual closely until the end of 2004 when the catchment was clear-felled. From January 2005 to December 2008 the simulations appear to consistently underestimate the streamflow and the Intermediate Zone ACRU more so than ACRU 3.31. An explanation for this may be that during the fallow period, the model is overestimating the total evaporation from the catchment. Other potential reasons for the under simulation of streamflow could be that there is a lag effect or that high levels of observed streamflow resulting from the original clearing of the wattle trees have not been reduced as quickly as the model predicts since replanting began. This apparent divergence between simulations and observed data, together with a change in the conditions of the catchment provide an excellent opportunity to verify model performance. It also shows that good model performance under a specific land-cover does not necessarily ensure good performance under different land-cover scenarios. This should be noted in climate change scenario modelling or land-cover change modelling.

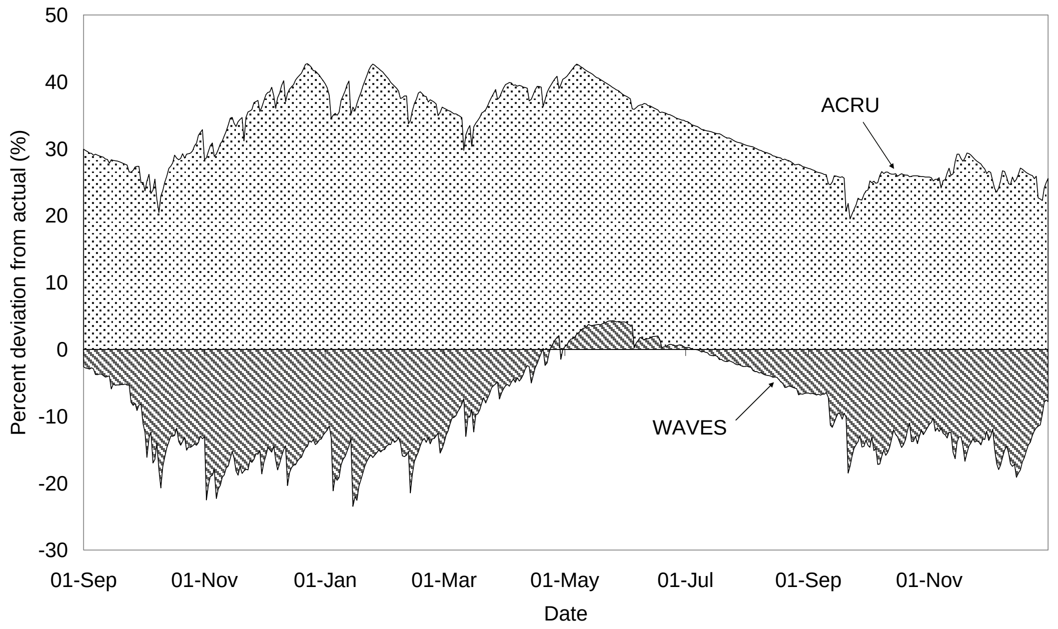


Figure 4.39. The percentage deviation from actual total profile water content over a 2.4 m depth for the ACRU and WAVES models at the Two Streams site from February to December 2007.

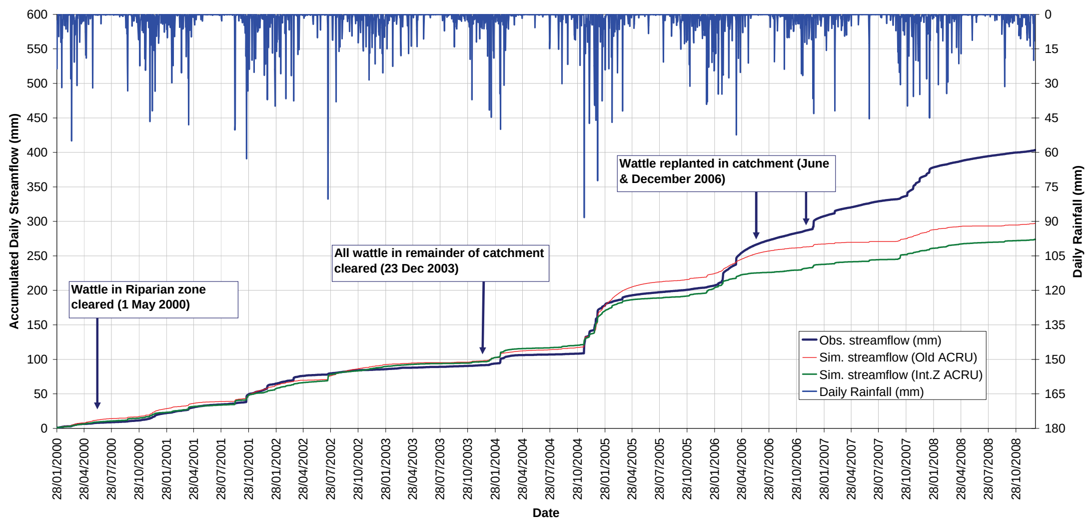


Figure 4.40. Time series of accumulated daily observed streamflow totals (mm) from Two Streams from January 2000 to December 2008 using ACRU version 3.31 and the new Intermediate Zone ACRU. Periods of significant land-use change are indicated.

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5. DISCUSSION AND CONCLUSION

In this study, the impact of *A. mearnsii* on soil hydrological processes was extended with additional detailed measurements of evaporation and soil water processes to improve our understanding of processes such as low flows and deeper soil water dynamics. The ever-growing demand for water makes it imperative that water resource management procedures and policies be wisely implemented and improved. To do this we need to advance our understanding of the impact of different crops on the water balance of catchments. The Department of Water Affairs and Forestry is deeply concerned by the need to link afforestation schemes to low flows in streams and rivers, since the allocation of land-use and re-allocation (changes in land-use) depend on accurate estimates of tree water-use impacts on low flows and groundwater resources (DWAF, 2002). In addition, allocation of water to stream flow reduction activities must also take into account the difference in water-use between forests and other crops and natural vegetation. A recent study on the comparative water-use of Eucalypts and Black Wattle trees in the Natal midlands at Seven Oaks (Jarmain and Everson, 2002) showed that total evaporation exceeded rainfall during the exponential growth phase of the trees (for example, the four year accumulated evaporation at the *Eucalyptus* site exceeded the rainfall by 75%). Studies in the Mpumalanga area (Dye *et al.*, 1997) have also demonstrated the reliance of *Eucalyptus* trees on soil water stored at depths beyond 8 m. This raises concerns over the impact of deep-rooted trees "mining" the soil water and groundwater reserves. The effect of excess evaporation over rainfall is ultimately transmitted into reductions in streamflow. Data from the Mokubulaan research catchments in Mpumalanga (Scott and Lesch, 1996), showed a five-year lag in streamflow recovery following clearfelling of *Eucalyptus grandis*, suggesting that abstraction of soil water from deep profiles may cause significant lags in streamflow response to management activities within the catchment. Internationally, Baldocchi and Xu (2007) investigated the Mediterranean Oak (*Quercus douglasii*) for similar reasons. The trees were able to survive extended periods without water and total evaporation was also found to exceed rainfall.

Currently, the regulation of water-use by forestry is based on estimates of plantation water-use over entire rotations at quaternary catchment scale (Gush *et al.*, 2002), which are average values that are not site or age specific. In addition, the model used did not account for soil water depletion at depths greater than 1.2 m. Gush *et al.* (2002) concluded that our understanding of the hydrological processes with regard to the water-use of trees from deep soil profiles was inadequate.

In this study we have described the processes of supply (rainfall) and demand (climate) for water and how they influence the evaporation process. From a biophysical standpoint, a forest or plantation cannot use more water through evaporation than is available from the input of rainfall minus runoff and infiltration of water below the root zone. To balance the water supply, plants can use a number of adaptive mechanisms (Baldocchi, 2007). On a short time scale plants can limit transpirational losses by closing stomata. In this study evidence of the *A. mearnsii* trees closing stomata on hot dry windy days was shown. These extreme events are rare however, and not likely to influence the water balance on an annual basis. On a longer time scale (millennia) plants can develop morphological and ecological adaptations that can lead to reduced transpiration, such as leaf drop or developing smaller leaves to convect heat more efficiently. When considering an exotic plant like *A. mearnsii*, imported from Australia in the last century, then this is clearly not a consideration. In addition, this study has shown that the *A. mearnsii* plants at Two Streams transpire at rates that are close to the Priestley-Taylor potential rate of evaporation (i.e. there was no evidence of reduced transpiration). The most plausible adaptation of the *A. mearnsii trees* is the development of deep roots that can access alternative sources of water. On an annual basis the Two Streams catchment received a nine-year average of 920 mm of precipitation (with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm). The upper range may appear adequate, but not all will be available to the trees as there will be losses due to interception, surface runoff and deep percolation past the root system. In dry years the tress will have to resort to an alternative source of previously stored soil water. In this study, the annual *ET* of the actively growing *A. mearnsii* was 1156 mm and 1171 mm and the rainfall 689 mm and 819 mm for 2007 and 2008 respectively. There was obviously a negative imbalance between the rainfall and *ET*.

Evaporation from the developing wattle plantation measured using a large aperture scintillometer was shown to exceed the rainfall by 46%, confirming the previous Bowen ratio measurements (Jarmain and Everson, 2002). Potential evaporation rates estimated using the Priestley-Taylor equation were on average only 5% lower than to the ET_{LAS}. The accuracy of the Priestley-Taylor equation has been validated by a review of 30 water balance studies in which it was commonly found that, in vegetated areas with no water deficit or very small deficits, approximately 95% of the annual evaporative demand was supplied by radiation (Stagnitti *et al.*, 1989). Morton (1983) notes that the value of 1.26, estimated by Priestley-Taylor, was developed using data from both moist vegetated and water surfaces. Morton has recommended that the value be increased slightly to 1.32 for estimates from vegetated areas as a result of the increase in surface roughness (Morton, 1983; Brutsaert and Stricker, 1979). The results of this study confirm these observations, since it was found that the available energy described 94% of the *ET* and that the Priestly-Taylor *ET* estimates were about 5% lower than *ET*. The implication of these results is that the wattle trees were using water at rates higher than the equilibrium rate throughout the year and that there was always some component of advective energy that increases the actual evapotranspiration. This means that true equilibrium potential evapotranspiration rarely occurred at the study site. Clearly water was not a limiting factor to the wattle growth during its first three years of development.

Internationally long-term catchment studies including actual measurements of all the water balance components are scare, while locally this represents a unique study on the impact of an exotic tree plantation on catchment hydrological processes. The only other long-term data set to include actual measurements of *ET* was collected from the Cathedral Peak CVI in *Themeda triandra* dominated grassland in the KwaZulu-Natal Drakensberg (Everson, *et al.*, 1998). This study provided a baseline against which the impacts of commercial forestry and other land-uses could be assessed. The daily total evaporation (ET_{LAS}) values for the *A. mearnsii* trees on cloudless summer days averaged 7 mm. On clear winter days the maximum total evaporation was approximately 2.4 mm day^{-1}. This contrasts with the *Themeda triandra* grassland evaporation rates measured in the Drakensberg of 7 mm in summer and < 1 mm in winter (Everson *et al.*, 1998). It is therefore the difference in the winter *ET* between grasses and evergreen trees that has the biggest impact on changing the catchment water balance. This will be particularly noticeable during the critical low flow (winter) periods.

The rainfall: runoff relationship (*Rr*) was 0.02 prior to clear-felling of the catchment in 2004. Following clear-felling the *Rr* increased to 0.08. This indicated increased runoff during the two-year fallow period and the first two years of wattle tree development. Forest management practices, therefore, have significant impacts on catchment water yields. The impact of clearing the riparian vegetation followed by clear-felling the catchment in 2004, resulted in a total gain in streamflow of 235 mm by January 2009.

In this study it was shown that the total input by precipitation was +1308 mm while the combined losses of *ET* and *Q* were -2120 mm. The measured change in soil water storage in the upper 2.4 m soil profile was -141 mm. Unaccounted for losses were therefore -671 mm or approximately -40 mm per month. These deficits in the water balance could only be supplied from the deep soil water stores beyond 2.4 m. These data are evidence that the wattle trees, whose roots went deeper than 4.8 m, were able to access the deep groundwater reserves. Other evidence for supporting this conclusion was:

- The electrical resistivity survey and borehole logs confirmed the presence of deep clays with high water contents to depths of 25 m. This represented a significant soil water storage reserve for access by deep rooted trees.

- Dry season borehole data showed a drop in water level of 1000 mm between 2007 and 2008, despite more rainfall in 2008. This drop in level was ascribed to the impact of the trees on the recharge rate.

- The *A. mearnsii* roots were found to depths > 4.8 m.

- The measurements of soil water and soil water potential showed a consistent drying out of the deeper soil profile as the trees developed.

These data are evidence that the wattle trees, whose roots went deeper than 4.8 m were able to access the deep groundwater reserves. These long-term hydrological studies in the Two Streams catchment, which included detailed process measurements, need to be continued to quantify the effects of the continued growth of the *A. mearnsii* trees on the catchment water balance and to document the response to impending global climatic change. Finally, the measurements together with hydrological models, which were shown to need further improvement, should be used together with satellite observations to up-scale the information across much wider areas.

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7. APPENDIX A. The two weekly intervals used to calculate effective height of the LAS beam above the canopy.

Period	Tree Ht	Beam Effective Height	Notes	Rough ness	Zero Disp Ht
19 August 2006-2 September 2006	0.45	6.476		0.045	0.301 5
3 September 2006-16 September 2006	0.65	6.251		0.065	0.435 5
17 September 2006-30 September 2006	0.70	6.194		0.07	0.469
1 October 2006-14 October 2006	0.80	6.078		0.08	0.536
15 October 2006-28 October 2006	1.15	5.656		0.115	0.770 5
29 October 2006-11 November 2006	1.48	5.222		0.148	0.991 6
12 November 2006-25 November 2006	1.71	4.881		0.171	1.145 7
26 November 2006-9 December 2006	1.81	4.716	Recalc Wsp	0.181	1.21
10 December 2006-23 December 2006	2.00	4.350/6.76	Recalc Wsp/raised receiver from 3.05m to 6.6m	0.2	1.34
24 December 2006-6 January 2007	2.24	6.474	Recalc Wsp	0.224	1.50
7 January 2007-20 January 2007	2.58	6.037	Recalc Wsp to 11 Jan	0.258	1.72
21 January 2007-3 February 2007	2.85	5.642		0.285	1.90
4 February 2007-17 February 2007	3.14	5.083		0.314	2.10

18 February 2007-3 March 2007	3.35	4.569/7.320	Raised transmitter from 3.23m to 6.25m	0.335	2.24
4 March 2007-17 March 2007	3.52	7.142		0.352	2.35
18 March 2007-31 March 2007	3.64	7.016		0.364	2.43
1 April 2007-14 April 2007	3.72	6.931		0.372	2.49
15 April 2007-28 April 2007	3.88	6.761		0.388	2.59
29 April 2007-12 May 2007	3.95	6.685		0.395	2.64
13 May 2007-26 May 2007	4.05	6.577	Raised Wsp from 6.3m to 9.3m	0.405	2.71
27 May 2007-9 June 2007	4.15	6.467/8.213	Raised receiver from 6.6m to 9.6m	0.415	2.78
10 June 2007-23 June 2007	4.30	7.916		0.43	2.86
24 June 2007-7 July 2007	4.44	7.769		0.444	2.96
8 July 2007-21 July 2007	4.65	7.545		0.465	3.10
22 July2007-4 August 2007	4.73	7.459		0.473	3.15
5 August 2007-18 August 2007	4.77	7.416		0.477	3.18
19 August 2007-1 September 2007	4.90	7.274		0.490	3.27
2 September 2007-15 September 2007	5.12	7.030		0.512	3.41
16 September 2007-29 September 2007	5.25	6.882		0.525	3.50
30 September 2007-13 October 2007	5.35	6.766		0.530	3.56
14 October 2007-27 October 2007	5.60	6.468		0.560	3.73
28 October 2007-10 November 2007	5.80	6.217		0.580	3.86
11 November 2007-24 November 2007	6.00	5.948		0.600	4.00
25 November 2007-8 December 2007	6.20	5.651		0.620	4.13
9 December 2007-22 December 2007	6.35	5.393		0.635	4.23
23 December 2007-5 January 2008	6.50	5.072		0.650	4.33
6 January 2008-19 January 2008	6.65	5.000	Estimated	0.665	4.43
20 January 2008-2 February 2008	6.85	4.950	Estimated	0.685	4.56
3 February 2008-16 February 2008	7.05	4.940	Estimated	0.705	4.70
17 February 2008-1 March 2008	7.35	4.930	Estimated	0.735	4.90
2 March 2008-15 March 2008	7.65	9.678	6 March-raised transmitter and receiver to 12.6m	0.765	5.10

16 March 2008-29 March 2008	8.05	9.289		0.805	5.37
30 March 2008-12 April 2008	8.35	8.995		0.835	5.57
13 April 2008-26 April 2008	8.60	8.749		0.860	5.73
27 April 2008-10 May 2008	8.90	8.451	30 April moved AWS to transmitter (12.6m)	0.890	5.93
11 May 2008-24 May 2008	9.05	8.301		0.905	6.03
25 May 2008-7 June 2008	9.10	8.251		0.910	6.07
8 June 2008-21 June 2008	9.15	8.200		0.915	6.10
22 June 2008-5 July 2008	9.20	8.150		0.920	6.13
6 July 2008-19 July 2008	9.40	8.147		0.940	6.27
20 July 2008-2 August 2008	9.50	8.047		0.950	6.33
3 August 2008-16 August 2008	9.70	7.844		0.970	6.47
17 August 2008-30 August 2008	9.90	7.640/9.22	27 Aug raised rec 15.6m (WS also raised)	0.990	6.60
31 August 2008-13 September 2008	10.10	9.024		1.010	6.73
14 September 2008-27 September 2008	10.20	8.924		1.020	6.80
28 September 2008-11 October 2008	10.30	8.824		1.030	6.87
12 October 2008-25 October 2008	10.40	8.724		1.040	6.93
26 October 2008-8 November 2008	10.50	8.624/10.047	6 November 2008 raised receiver to 18.6m (Wind speed also raised)	1.050	7.00
9 November 2008-22 November 2008	10.60	9.946		1.060	7.07
23 November 2008-6 December 2008	10.80	9.741		1.080	7.2
7 December 2008-20 December 2008	10.90	9.639		1.090	7.27
21 December 2008-3 January 2009	11.00	9.536		1.100	7.33
4 January 2009-17 January 2009	11.10	9.432		1.110	7.40
18 January 2009-31 January 2009	11.15	9.38		1.115	7.43
1 February 2009-14 February 2009	11.2	9.328		1.120	7.47

From 26/11/2006 to 11/1/2007 up scaled windspeed sensor ht from 2 m to 6.3 using log law, thereafter Windspeed sensor raised to 6.3m

8. APPENDIX B. Borehole logs.

Borehole no:	KZN07168	Map ref:		Date Started:
Region:	KwaZulu Natal	Latitude:	30º 39' 03" E	Date Finished:
District:	Umzinyathi	Longitude:	29º 12' 25.6" S	VBA Groundwater
Farm:	Mistley 2034	Water level (m,b,g,l):		EC:
Village:	SevenOaks	Collar height (m):		Ph:
Altitude (m):		Air lift yield (l/s) :		

Water Strikes:	1	2	3	4	5	
Depth (m)						
Yield (l/s)						

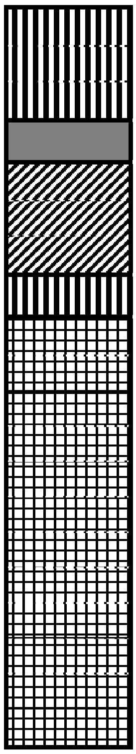
Casing Detail:							
From/To (m):	16						
Type (S/P)	S	P					
Diameter (mm):	165						

Sanitary Seal: DRILL CUTTINGS:

B/H Diam	
	215mm
	165mm

Depth Lithology, Colour, Grain Size, Weathering, etc.

Depth	b/h diam	casing diam
10		
	215mm	165mm
20		
30		
40	165mm	



Description

0-6m Red Brown Clay

7-8m Light Red Brown Clay

9-14m Light Brown Clay

15m Grey Fine Grained Shale

16-40m Grey Granite

E.O.H

Borehole no:	**KZN07169**	**Map ref:**	
Region:	**KwaZulu Natal**	**Latitude:**	**30º 38' 49.7" E**
District:	**Umzinyathi**	**Longitude:**	**29º 12' 20" S**
Farm:	**Mistley 2034**	**Water level (m,b,g,l):**	
Village:	**SevenOaks**	**Collar height (m):**	
Altitude (m):		**Air lift yield (l/s) :**	**0.5**

Water Strikes:	**1**	**2**	**3**	**4**	**5**
Depth (m)	**31**	**41**			
Yield (l/s)	**Wetspot**	**0.5**			

Casing Detail:							
From/To (m):	**25**						
Type (S/P)	**S**	**P**					
Diameter (mm):	**165**						

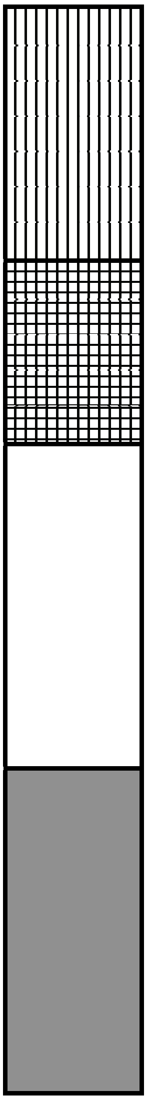
Sanitary Seal: | **DRILL CUTTINGS:**

B/H Diam	**215mm** **165mm**

Depth | **Lithology, Colour, Grain Size, Weathering, etc.**

Depth	b/h diam	casing diam
0–25	215mm	165mm

10
20
30
40
50
60



Description

0-14m Red Brown Clay

15-24m Light Brown Clay

25-43m Grey Fine Grained Shale

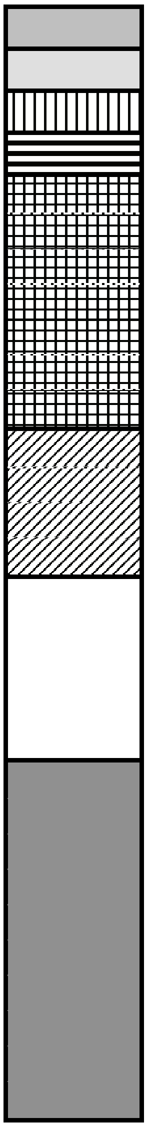
43-60m Grey Granite

E.O.H

Borehole no:	**KZN07170**			**Map ref:**		
Region:	**KwaZulu Natal**			**Latitude:**	**30º 39' 5.1" E**	
District:	**Umzinyathi**			**Longitude:**	**29º 12' 12" S**	
Farm:	**Mistley 2034**			**Water level (m,b,g,l):**		
Village:	**SevenOaks**			**Collar height (m):**		
Altitude (m):				**Air lift yield (l/s) :**		
Water Strikes:	**1**	**2**	**3**	**4**	**5**	
Depth (m)						
Yield (l/s)						
Casing Detail:						
From/To (m):	**22**					
Type (S/P)	**S**	**P**				
Diameter (mm):	**165**					
Sanitary Seal:				**DRILL CUTTINGS:**		
B/H Diam	**215mm** **165mm**					

Depth **Lithology, Colour, Grain Size, Weathering, etc.**

Depth	b/h diam	casing diam
0–22 (10, 20)	**215mm**	**165mm**
22–40 (30, 40)	**165mm**	
40–60 (50, 60)		



Description

0-1m Brown Clay

2-3m Red Brown Clay

4 Brown Clay

5-7 Light Brown Clay

8-22 Red Brown Clay

32-40m Grey Shale

41-60 Granite

E.O.H

p